The Effect of Development on Nitrogen Loading on St. John, U.S. Virgin Islands

By

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Abstract

The majority of St. John's land and coast is a National Park and is protected by the federal government. In spite of these restrictions, the population of St. John has risen in the past fifteen years as has the number of tourists that visit the island. A possible side-effect to the growing population is increased nitrogen loading to the bays, which can impact the benthic habitat.

The purpose of this thesis is to evaluate the extent of the effects of human developments on nitrogen loading of the bays on St. John, U. S. Virgin Islands. This is accomplished by taking nitrogen samples of the bays, using ArcGIS and the Nitrogen Loading Model to estimate the nitrogen loading of the bays, and correlating historical nitrogen concentrations with increases in population. While the analysis of nitrogen samples of the bays is inconclusive, the Nitrogen Loading Model estimates that bays with greater levels of development have higher amounts of nitrogen loading. Historical nitrogen concentrations show little relationship between the level of development of the watersheds and the concentration of nitrogen within the bays. Overall, there is little evidence that nitrogen loading from development is causing excessive nitrogen loading.

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1 INTRODUCTION

Around the world, development of coastal areas is having adverse impacts on the health of near-shore marine ecosystems (Millennium Ecosystem Assessment, 2005). Discharge of pollutants from point and non-point sources in coastal watersheds results in impaired water quality of the receiving estuaries and coastal waters. Some of the major issues related to declines in water quality within coastal areas include loss of biodiversity, eutrophication, harmful algal blooms, heavy metal and toxic pollution, and increased health risk through the spread of pathogens. About 40% of the world's population now lives within 100 km of the coast, and that proportion is expected to rise (Millennium Ecosystem Assessment, 2005). As more and more people relocate to coastal areas, their impact will become noticeably more severe.

Over the past few decades, the United States Virgin Islands (USVI) have seen an unprecedented rise in human development as an increasing number of tourists travel from around the world to vacation in the warm weather and exotic landscapes for which these islands are well known. In order to meet a rising demand, developers have been constructing new homes at increasing rates (USVI Bureau of Economic Research, 2006). Additionally, the islands are becoming a popular destination for permanent relocation and retirement among people from temperate regions (Eastern Caribbean Center, 2002).

Increases in nutrient discharge from septic system seepage and other anthropogenic sources can drive aquatic marine ecosystems to a state of eutrophication. This impaired state is caused by over-production of algae, the growth of which is usually limited by the availability of nitrogen in marine systems. Eutrophication results in poor water quality conditions such as low dissolved oxygen levels and heightened turbidity. As algae proliferate due to greater nitrogen availability, the water column becomes increasingly turbid and less light reaches benthic primary producers such as seagrass and corals.

The purpose of this thesis is to determine nitrogen loading rates within different bays on the U.S. Virgin Islands (USVI). Specifically, this thesis is to address if developments on the island are contributing significantly to the nitrogen loading and whether this is a problem. This thesis was completed in conjunction with a broader assessment of the impact of nitrogen on the USVI coral reefs completed as a Masters of Engineering group project within the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology. This and the following sections were taken from the project report and are the result of a collaboration with William Detlefsen, Helen McCreery, and Jeffrey Walker (Detlefsen et al., 2007).

2 BACKGROUND

The following sections give an introduction to the thesis and the project upon which the thesis is based. These sections include 1) an overview of the U.S. Virgin Islands; 2) information about the coral reefs; 3) an overview of nitrogen; 4) the experimental design of the project; and 5) the objective for the thesis.

2.1 U.S. Virgin Islands

This section gives an overview of the U.S. Virgin Islands (USVI). It begins with the geography and climate of the islands, followed by brief history of the island. The final part documents the development of the island within the past twenty years.

2.1.1 Geography and Climate of the U.S. Virgin Islands

The U.S. Virgin Island are located about 80 km east of Puerto Rico in the north-eastern region of the Caribbean Sea (18° 20' N 64° 50' W) (Figure 2.1). The USVI are a territory of the United States and encompass three main islands—St. John, St. Thomas, and St. Croix—in addition to a number of smaller, uninhabited islands (Figure 2.1). The total territorial area is 1,910 km^2 of which 346 km^2 is land surface bounded by 188 km of coastline (Seitzinger, 1988). The island of St. John, which is the smallest of the three, is 52 km^2 in area and reaches a maximum elevation of 390 m (Jeffrey et al., 2005; United States Geological Survey, 2004). The region is divided into two geologically-dissimilar island archipelagos: the Lesser Antilles, which includes the US Virgin Islands and those islands to the south and east, and the Greater Antilles, which includes Puerto Rico and the islands to the north and west (Jeffrey et al., 2005).

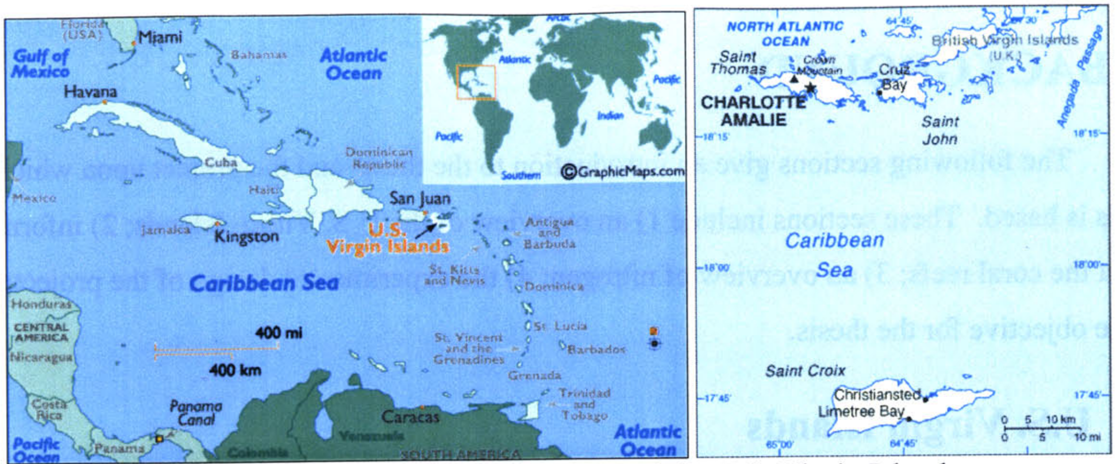

Figure 2.1: Regional and local maps of the U.S. Virgin Islands
Source: (World Atlas, 2007)

The climate in this region is subtropical and generally stable with monthly-average mean air temperatures ranging from 24 to 28°C (76 to 82°F) throughout the year (Southeast Regional Climate Center, 2005). The average daily maximums and minimums for each month range from 3 to 5°C about the mean which suggests a fairly low daily temperature fluctuation throughout the year (Southeast Regional Climate Center, 2005). The average temperature of coastal waters ranges from 25 to 28°C (77 to 84°F) (Department of Planning and Natural Resources, 1980).

Total annual precipitation averages about 1,100 mm (45 inches) with the rainiest months occurring between August and November (Southeast Regional Climate Center, 2005). A large portion of annual rainfall is produced during the largest rainfall events of the year. Most rainstorms have short durations and produce only a couple millimeters of water at a time. Due to the warm, dry climate, potential evapotranspiration is very high in this region and generally exceeds precipitation. According to one estimate, about 94% of rainfall returns to the atmosphere by evapotranspiration, leaving just 6% of rainfall to recharge groundwater or become surface runoff (Carr et al., 1990). As a result of the high rates of evapotranspiration, most storms do not produce any surface runoff and no permanent streams exist on St. John. Groundwater recharge occurs mainly after heavy storms that saturate the soil and result in drainage to fractured bedrock below.

Due to their latitude and proximity to the Gulf Stream, the USVI are subject to frequent tropical storms and hurricanes. Large storms can cause flooding and high rates of soil erosion leading to heightened sediment loading and increased turbidity of coastal bays. Significant reef damage can also result from high-energy wave impacts (Jeffrey et al., 2005).

2.1.2 History of the U.S. Virgin Islands

Before the arrival of the Europeans in the 15^{th} century, the Virgin Islands were inhabited by the Ciboney, Caribs, and Arawak tribes. Although little is known about these native people, they are believed to have ancestral ties to tribes in South America. The first Europeans to set foot on the islands were led by Christopher Columbus, who named the islands "The Virgins" in 1493, in reference to the legend of Saint Ursula and her eleven-thousand virgins.

Over the following two centuries, Europeans caused significant hardship for the native people through the introduction of new diseases, continuous raids, and enslavement of native people. By the mid-17^{th} century, the native island populations had been decimated and the Europeans began to establish permanent settlements. Although the islands were occupied by a number of European countries, the Danish eventually assumed complete ownership of the islands, which they found to be an ideal location for tobacco, sugar and cotton plantations.

Thousands of slaves were sent from Africa to work in the plantation fields, which caused an imbalance in population: in 1725 there were a total of 324 Europeans commanding 4,490 slaves (Maybom & Gobel, 2002). In 1733 the slaves revolted on the island of St. John and drove the Danish settlers off the island, but the insurrection was halted by military force and the island was again placed under colonial control. Rebellions were not infrequent until July 3, 1848 when slavery was abolished.

Throughout the 19^{th} century, sugar was the primary export of the island. But as the years passed, demand for sugar began to decrease and sugar production became less and less profitable. Poor housing conditions led to widespread sickness and a decline in the population. Costs of maintaining the islands led the Danish government to try to sell the islands in 1867 and 1906 but political and national concerns prevented the transaction. During World War I, the conditions on the islands worsened due to further drops in the demand for sugar. The United States eventually purchased the three islands of St. Croix, St. John and St. Thomas from the Danish in 1917.

Although conditions were slow to improve under US control, tourism began to grow after World War II with the construction of a number of resorts on the islands. In 1952, Laurance Rockefeller purchased a large portion of the island of St. John and began constructing roads, water pipes, and electrical facilities to create a luxury campground. Over the following few decades, the islands emerged as one of the most popular vacation destinations worldwide.

Today, tourism is the main industry on the USVI with approximately 80% of the economy specializing in the service-related industries (Lexdon Business Library, 2006). The Gross Territorial Product (GTP) has steadily increased by about 6% annually to 2.6 billion in 2004 (USVI Bureau of Economic Research, 2005). Between 1996 and 2000, the number of visitors to the three islands increased by 35% to 2.4 million annually, 85% of which visited the two smaller islands of St. Thomas and St. John (Eastern Caribbean Center, 2002). Tourists are attracted to the pristine beaches, exotic landscapes, and easily accessible coral reefs. Protection of these valuable natural resources is critical for the economic well-being of the USVI.

2.1.3 Development in the U.S. Virgin Islands

Because the Virgin Islands are a major tourist destination, the level of habitation and development are greater than islands not focused on tourism. Developments for this project are considered as any type of large, man-made structure such as a building, road, or dock. Compared to the other islands of the USVI, St. John has far fewer developments due to Virgin Islands National Park, which covers more than half of the island. Even so, there are still many developments on the island that can affect the coral reefs. The following sections describe the history of the national park, the resorts, the other developments on the island, the historic trend of development within the past fifteen years, and the impact of developments within the bays in terms of sediment and nutrient loading.

2.1.3.1 Virgin Islands National Park

Unlike the other islands of the Virgin Islands, over half of St. John is designated a national park which limits the extent of development in some areas (Uhler, 2007). The Virgin Islands National Park was established on August 2, 1956, and protected the majority of the island (9,485 out of the 12,500 acres of St. John). On October 5, 1962, the park was expanded to include 5,650 submerged acres to protect the coral reefs around the island, and in 1978 Hassel Island was included under its protection. Today, the park encompasses 14,689 acres of island and submerged areas. The national park is one of the major tourism sites on the island: in 2001, the park received 71,462 visitors (Uhler, 2007).

2.1.3.2 Resorts

Like other islands in the region, the largest single developments are resorts. There are two major resorts on the island: Caneel Bay and the Westin Resort. Caneel Bay is part of the Rosewood Resorts chain and is located on the eastern side of the island (Caneel Bay, 2007). It was founded by Laurence Rockefeller in 1952, a time when only 400 individuals inhabited St. John. In 1955, Rockefeller helped build the island's infrastructure by providing roads, electricity, and fresh water to the inhabitants. He also donated 5,000 acres to the federal government, which would later be used to start the national park. Today, Caneel Bay occupies 170 acres and has 166 rooms.

The Westin Resort was originally the Hyatt Regency Resort until 1995 when hurricanes caused severe damage to the facilities and ownership was transferred to Westin Hotels and Resorts (Lloyd, 2007). Constructed in 1986 at Great Cruz Bay, the resort currently has 174 rooms, 92 suites, and 67 villas within 47 acres (Pira, 2007).

2.1.3.3 Other development

The two regions that contain the most development on St. John are Cruz Bay and Coral Bay, with the majority of the population at Cruz Bay. Development for this project is classified into buildings and roads. Cruz Bay is the main harbor and is the location for the majority of businesses on the island. A wastewater treatment facility is located at Cruz Bay and most buildings within the Cruz Bay district are connected via a sewer system. The treatment plant uses secondary treatment and discharges the effluent approximately one mile from the coast. Coral Bay contains less development and fewer central facilities.

Homes are located throughout the island with the exception of the central and southern regions that are part of the National Park and contain few buildings. All homes are connected to the electrical grid but few houses outside of Cruz Bay are connected to the water or wastewater system. Water is generally purchased from trucks, although some homes have rain collection systems installed in their homes. Most homes have individual septic systems installed.

Roads are generally paved and are concentrated on the eastern side of the island. Two roads (North Shore Road and Centerline Road) connect Cruz Bay to Coral Bay. Because of the relief on the island, large portions of the hills have to be carved out in order to construct the roads. A large portion of the roads are paved but there are many roads, especially in residential areas, which remain unpaved.

2.1.3.4 Trends in development

Yearly data was examined from the U.S. Virgin Islands Bureau of Economic Research (Mills et al., 2006) to evaluate the growth of development on St. John. Figure 2.2 shows the census populations of St. John and the annual number of visitors, and Figure 2.3 shows the annual fuel and energy consumption of the Virgin Islands. Within the past fifteen years population has increased by 10.6%, the number of visitors to the island has increased by 20.2%, and the fuel and energy consumption has increased by 23.5% and 29.9% respectively. Because of the national park on the island, development is more constrained than on the other Virgin Islands, but the general upward trend suggests that there will be increasing construction for years to come.

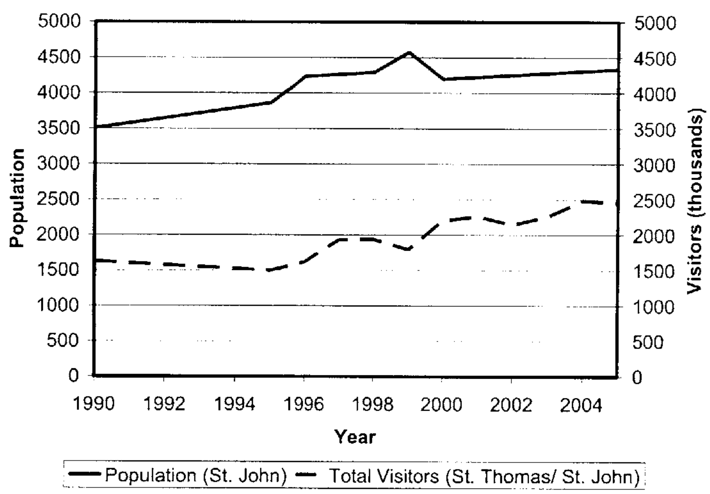

Figure 2.2: Census population and annual visitors
Source: (Mills et al., 2006)

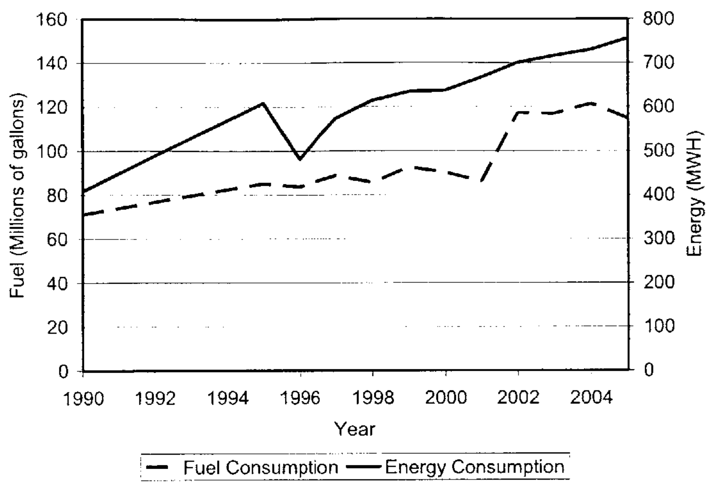

Figure 2.3: Census fuel consumption and energy consumption
Source: (Mills et al., 2006)

2.1.3.5 Impact of development on the coral reefs

Many studies have expressed serious concern over the impact of coastal developments on the coral reefs. Approximately 58 percent of coral reefs in the region are threatened by human activity (UNEP, 2006). These threats are the result of an increase in tourism over the past fifty years, which has lead to the construction of more developments on the nearby islands to attract and house more visitors.

One of the primary concerns about the gradual urbanization of coastal watersheds is its impact on sediment and nutrient loading rates. The effect of developments on the land surface is that it replaces vegetation coverage with impervious surfaces. Vegetation holds soil in place through its roots that brace the soil and hold water. It is also an important sink for nutrients. Impervious surfaces have the opposite effect of vegetation by preventing water from percolating into the ground, thereby increasing the volume of runoff during storms. Increasing runoff flow carries greater sediment and nutrients into the bays. Developments also remove natural sinks for nutrients, allowing greater concentrations to flow into receiving water bodies. Roads, especially unpaved ones that have no stormwater capture system, contribute greatly to sediment loading rates within watersheds.

Construction requires that large portions of the ground must be cleared of vegetation and excavated. The excavated material is deposited in ravines that can flood during large storms and release highly turbid water into the bays. Construction on St. John has a greater impact on sediment loading on St. John than many other places because of the slopes on the island. The island has many high-grade slopes that must be excavated into flat slopes to allow construction of buildings or roads. As the cut into the hill widens, a greater proportion of soil has to be excavated due to the triangular shape of the cut; doubling the width of road quadruples the amount of earth needed to be removed. Reducing the sizes of roads and buildings substantially reduces the amount of soil needed to be excavated.

Wastewater effluents from water treatment facilities and septic tanks contain high concentrations of nutrients which can lead to excess nutrient loading and eventual eutrophication of the bays (UNEP, 2006) (see Section 2.2.2.6). While the wastewater treatment facility on St. John disposes its effluent a mile offshore of the island away from the bays, the septic tanks are the primary effluent treatment system for the majority of homes on the island. Effluent from septic tanks is released below the ground and disperses into the soil. It eventually travels downgradient via groundwater flow and is released at the seepage face into the receiving water body. As the population increases on the island, more waste is produced which can dramatically increase nitrogen loading rates for the bays.

Recent studies have shown that coastal developments have been having an adverse effect on coral reefs. A recent study conducted by Lotze et al. (2006) examined fossil records at various estuaries to quantify the number of species inhabiting the estuary at different time periods. Twelve estuaries in Europe, North America, and Australia were examined and the numbers of species were compared to today's relative abundance of species. The study found that there has been an over-90% reduction in the number of important species, as well as over 65% of the wetland habitat (Lotze et al., 2006). Estuaries also exhibited significant water quality degradation. These losses accelerated between 1900 and 1950 but have recently leveled off due to awareness of protecting the estuaries.

Another study was conducted by Padolfi et al. (2003) that examined the historical impact of human development on the coral reefs. The ecological histories of 14 coral reefs were compiled from various data sources extending back thousands of years to analyze the extent and rate of degradation of the reefs. The level of degradation was compared with the level of technology of the inhabitants living at the coasts to the reefs. The study found that as the level of technology of the coastal inhabitants increased, the ecological state of the reefs declined, with the highest decline occurring with the appearance of modern technology. The study was also conducted for the coral reefs at the Virgin Islands and the health of the reef was ranked as "severely degraded" (Pandolfi et al., 2003).

2.2 Coral Reefs

One of the focuses of the group project is to evaluate the health of the coral reefs. The following sections describe the ecology and biology of the coral reefs, and the threats and dangers facing coral reefs today.

2.2.1 Ecology and Biology of Coral Reefs

Coral reefs are some of the most productive and diverse ecosystems in the world. The mean aerial rate of net primary productivity is higher than any other type of ecosystem, including tropical rain forests (Geyer, 1997). These high rates of productivity are due in part to a highly efficient cycling of nutrients and energy through a complex food web. Common to all reef ecosystems are spatially complex reef structures which provide niche habitats for the wide diversity of organisms that make up this food web. The formation of these structures is driven by the growth and erosion of coral skeletons.

Coral are animals resembling sea anenomae that build carbonate shells, known as coralline cups, to protect and support their internal organs (Figure 2.4). The shell is open-ended allowing the head of the coral, known as the polyp, to emerge and feed on free-floating planktonic animals from the surrounding water. Within the tentacles of these polyps reside symbiotic, single-celled dinoflagellate algae called zooxanthellae, which are mainly of the genus *Symbiodinium*. These algae produce organic carbon by photosynthesis which they supply to their host coral in exchange for dissolved carbon dioxide and nutrients (Mann, 2000).

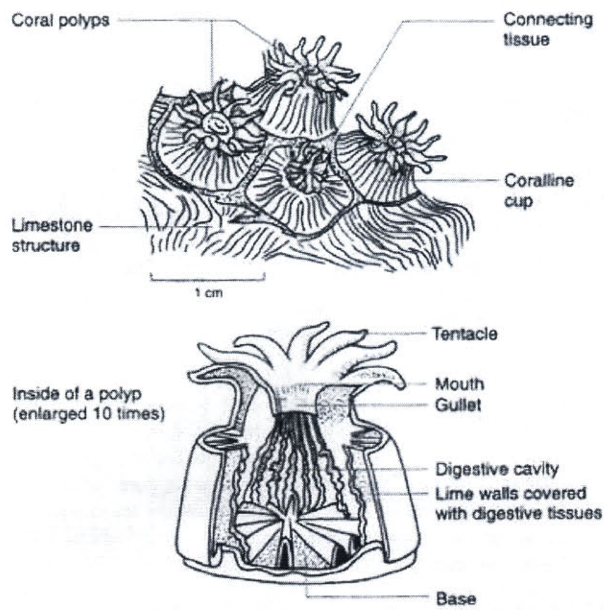

Figure 2.4: Anatomy of coral polyps
Source: Mann (2000)

Throughout most of its lifecycle, the coral remains attached to a fixed substrate, usually the reef itself. When a coral dies, its skeleton remains and physical disturbances such as wave impacts and burrowing by organisms known as bioeroders break the skeleton into smaller and smaller pieces. Over time, these small pieces of calcium carbonate accumulate on the reef surface resulting in growth of the reef substrate. Numerous species of encrusting algae also contribute to the formation of a reef structure by depositing thin sheets of limestone. These free-living algae can account for 17-40% of total carbonate deposition (Mann, 2000). Other species of non-encrusting algae including small, filamentous forms are often found in reef ecosystems and form the short algal turf which is a key food supply for herbivores (Gleason, 1998). Healthy coral reefs are generally referred to as coral-CCA-short-turf communities where CCA is an abbreviation for crustose coralline algae.

Coral reefs are typically located in oligotrophic, or nutrient-poor, marine environments and thus rely heavily on efficient nutrient cycling within the ecosystem to maintain their high rates of productivity (Smith, 1984). A highly complex food web ensures the uptake and cycling of all available nutrients. The interactions between trophic levels may have significant impacts on the composition of the reef building community. For example, there is evidence that the abundance of herbivores may control the colonization of macroalgae on coral substrate (Belliveau & Paul, 2002).

Coral reef formation is highly sensitive to temperature and generally requires mean annual water temperatures of at least 18°C (64°F) (Mann, 2000). This sensitivity confines reefs to the tropical and subtropical regions between the Tropics of Cancer and Capricorn. Since reefs depend on the growth of photosynthesizing organisms at the base of the food web, these ecosystems exist in relatively shallow regions such as continental shelves, island coastlines and atolls where light is able to penetrate through the entire water column. The three major types of coral reefs are fringing reefs, barrier reefs and atoll reefs (Figure 2.5). Fringing reefs occur near the coastline of continents or islands; barrier reefs are located further from shore and form lagoons between the reefs and the mainland; atoll reefs develop on atolls which are isolated and submerged land masses resulting from the subsidence of a former island. The coral reefs around St. John are mainly fringing reefs and are found close to shore around most of the island (Drayton et al., 2004).

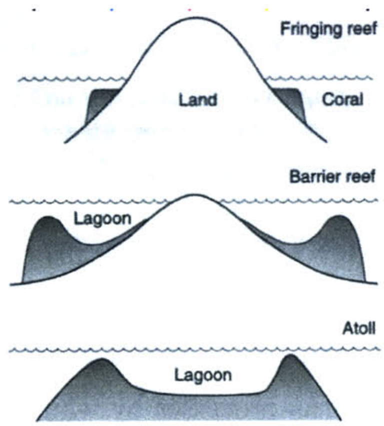

Figure 2.5: Major types of coral reefs
Source: Mann (2000)

2.2.2 Threats to Coral Reefs: Stressors, Bleaching, and Coral Death

There are many different factors affecting the health of coral. Some threats to coral health are caused naturally within the environment, while others are caused or facilitated by human activity. The following sections discuss the causes of bleaching, the effect of climate change, the different diseases, the consequences of physical damage, the impact of sedimentation, the danger of eutrophication, and the state of the coral reefs on St. John.

2.2.2.1 Coral bleaching

Coral are sensitive to a number of environmental stressors including temperature, turbidity, pH, and salinity (Jeffrey et al., 2005). In response to chronic or acute episodes of stress, coral may lose their pigmentation and turn white—an event known as coral bleaching. This loss of color is an indication that the coral have expelled the symbiotic zooxanthellae algae that live within their polyps. Without zooxanthellae, only the calcium carbonate shells of the coral are visible, giving them a white appearance (Figure 2.6).

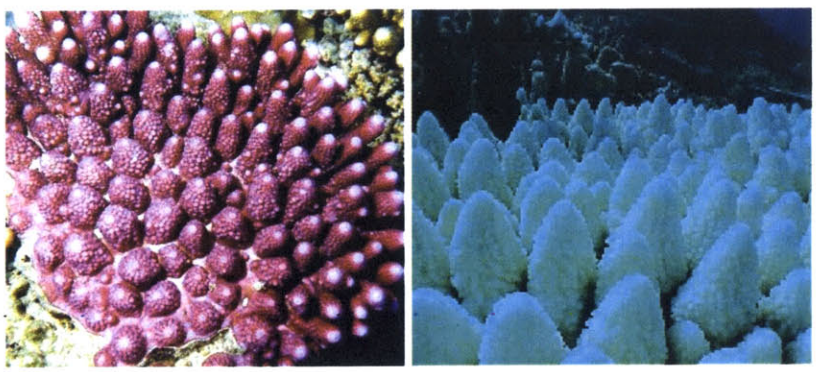

Figure 2.6: Comparison of healthy and bleached coral
(left: healthy coral; right: bleached coral)
Source: (Great Barrier Reef Marine Park Authority; Seaman)

Bleaching occurs when coral are under prolonged or acute episodes of stress. If the stress is short-lived, coral are capable of repopulating their zooxanthellae colonies; but if the zooxanthellae do not recover, the coral will be unable to survive from the loss of this symbiotic relationship. Although the biochemical processes by which the coral expel their zooxanthellae are not well understood, some speculate that under stressful conditions the symbiosis becomes less beneficial for one or both species (Brown, 1997). Expulsion of zooxanthellae is not the only possible cause of coral bleaching; any loss of the symbiotic algae, including death, will result in the loss of pigmentation and is therefore considered bleaching. There are many factors that contribute to coral bleaching and the loss of coral reefs, most of which are directly related to anthropogenic activities.

2.2.2.2 Climate change

Perhaps the most widespread threat to coral reefs is rising seawater temperature due to global climate change (Jeffrey et al., 2005). Research has repeatedly shown that rising temperature can cause massive, episodic coral bleaching and death (Edmunds, 2004; Knowlton, 2001). Some evidence suggests that in addition to coral bleaching, climate change may have other potentially significant impacts on reef ecosystems. Although a gradual rise in sea temperature may not cause a bleaching event, it may still change the ecology of the reef (Edmunds, 2004). Under a new temperature condition, different coral species will dominate and reef diversity may suffer. Edmunds (2004) suggests that higher temperatures may allow coral that produce small, simple colonies to outcompete coral that build large, complex skeletons. Although rising sea temperature poses a clear threat to the coral reefs on St. John, the focus of this project is on local rather than global stresses.

2.2.2.3 Disease

Another major stress affecting coral is disease, which has recently become a particularly severe problem in the Caribbean (Drayton et al., 2004; Weir-Brush, Garrison, Smith, & Shinn, 2004). The disease that appears to be the most devastating to Caribbean coral is white band disease (Drayton et al., 2004) (Figure 2.7). White band disease is characterized mainly by a visible white band that proceeds through living coral leaving behind bleached remains.

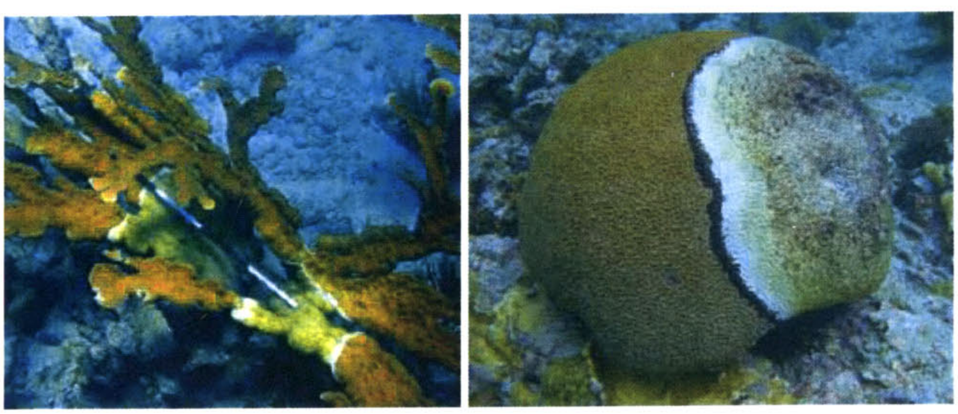

Figure 2.7: Common coral diseases.
(left: White Band Disease; right: Black Band Disease)
Source: (Jeffrey et al., 2005)

The cause of white band disease is still being debated, but recent studies suggest a link between an increase in coral disease and an increase in the severity of African dust storms, which may be related to global climate change (Weir-Brush et al., 2004). In general, few coral diseases have been fully characterized; but studies on one disease in particular, Aspergillosis, have shown the potential cause to be the terrestrial fungus *Aspergillus sydowii*. Weir-Brush et al. (2004) were able to show that incidents of Aspergillosis in Caribbean coral were caused by the presence of *Aspergillus sydowii* which originated from Africa.

Other studies suggest that rates of coral disease may be related to sewage outflow. A distinct correlation was shown between two coral diseases, black band disease (Figure 2.7) and white plague disease, to sewage exposure (Kaczmarsky, Draud, & Williams, 2005). Although little is known about the mechanism by which these diseases affect coral, black band disease appears to be similar to white band disease, as it also leaves dead coral behind as it progresses.

2.2.2.4 Physical damage

The most direct cause of coral death is physical damage by hurricanes or collisions with anchors or boats. Since reefs develop at very slow rates, recovery from physical damage, or any coral death, typically occurs over very long time scales—hundreds of years for a large, well-established reef. Given the frequency of tropical storms and hurricanes in the Caribbean, the reefs in this area are particularly prone to damage from storm events.

2.2.2.5 Sedimentation

One of the most direct impacts of coastal development on coral reefs is through increases in the transport of sediment from the land surface to coastal waters. This transport is the focus of this study. During construction of new developments, large amounts of soil are typically excavated and relocated to form level foundations. This loose soil is highly susceptible to being transported during rain events that cause surface runoff.

High sedimentation rates can cause stress and even death of coral in a number of ways. The most direct mechanism is for the sediment to simply bury the coral, effectively restricting access to free-floating phytoplankton, the main food source for coral, and to light, which is needed for survival of the zooxanthellae (Bothner, et al., 2006). However, sediment may affect coral well before loading rates reach this stage.

Sedimentation causes an increase in turbidity, which in turn reduces light penetration through the water column. As a result, less light reaches the photosynthesizing zooxanthellae that live symbiotically with the coral. Additionally, in most cases, increases in sediment loads are associated with increases in nutrient loads leading to eutrophication.

A study on the effect of chronic stress from sediment load on coral reefs in Singapore found that coral cover decreased by about 50% over the past three decades (Dikou & van Woesik, 2006). While some of the coral still survive, the dominant species are typically found in much deeper, more naturally turbid waters; the ecology of the reef has therefore changed as a result of the sediment stress.

2.2.2.6 Eutrophication

Another significant threat to coral reefs is eutrophication caused by excessive nutrient enrichment. The functioning of any ecosystem depends on the supply of organic biomass from primary producers such as plants and algae. These organisms convert inorganic carbon, usually carbon dioxide, to organic carbon using biochemical carbon fixation pathways such as photosynthesis. In order to build new biomass from inorganic carbon sources, producers need nutrients such as nitrogen, phosphorous, sulfur and calcium. The amounts of each nutrient needed per unit of carbon fixed vary by organism. Compared with aquatic producers, terrestrial primary producers generally require much more carbon relative to other elements due to greater carbon-rich structural content such as wood. In marine ecosystems, algae are composed of carbon, nitrogen and phosphorous atoms in an approximate ratio of 106 C : 16 N : 1 P, which is known as the Redfield ratio (Redfield, 1958). Generally, the ratios of elements available in the environment differ from the ratios required by primary producers to produce new biomass. If one element is less abundant relative to the others according to the Redfield ratio, algal growth will be limited by the availability of that element which is then considered the limiting nutrient of the ecosystem.

The two most common limiting nutrients in aquatic ecosystems are phosphorous and nitrogen (Smith, 1984). Phosphorous is generally the limiting nutrient in most freshwater ecosystems while nitrogen is usually limiting in marine ecosystems (Howarth & Marino, 2006; Smith, 1984). The addition of a limiting nutrient to an ecosystem stimulates growth of primary producers more than the addition of any other nutrient. Therefore, the enrichment of marine ecosystems with nitrogen tends to boost primary production. The system is said to be in a state of eutrophication if the rate of primary production results in significant deterioration of water quality.

Around the world, eutrophication is having significant impacts on aquatic ecosystems by causing oxygen depletion, loss of biodiversity, increased frequency of harmful algal blooms, and alterations in species composition (Scavia & Bricker, 2006). Typically, the enrichment of limiting nutrients causes high growth rates of suspended- and macro-algae (Duarte, 1995). Proliferation of algae from nutrient addition increases the turbidity of the water column and decreases light penetration to benthic primary producers such as seagrass or corals—a similar effect as elevated sediment loads. Under eutrophic conditions, competition between algae and other primary producers results in a phase shift from dominance by one type of primary producer to another type, such as from seagrass to macro-algae, which can have significant rippling effects throughout the rest of the ecosystem (Duarte, 1995).

Coral reefs are unique among aquatic ecosystems due to their high rates of primary production, significant biodiversity, and close proximity to oligotrophic ocean water. These characteristics result in less well-understood dynamics regarding phase shifts caused by nutrient enrichment. Nutrient enrichment has been shown to cause phase shifts from healthy coral-CCA-short turf communities to macrophyte-tall turf systems, where the small filamentous algae turfs are replaced by large filamentous and macrophytic algae (Lapointe, 1997). However, there is great debate in the literature over the cause-and-effect relationship between nutrient enrichment and phase shifts between these two types of benthic communities (Szmant, 2002).

One of the most ambitious field experiments to date on nutrient enrichment is the Effect of Nutrient Enrichment on Coral Reefs (ENCORE) project in the Great Barrier Reef (Koop et al., 2001). Four treatments of nutrients (a control with no nutrient addition, nitrogen addition only, phosphorous addition only, and both nitrogen and phosphorous addition) were applied to twelve individual coral reefs. The researchers concluded that reef organisms were indeed affected by nutrient enrichment, though the impacts were not severe. The only direct effects of nutrients on coral reefs were on the reproductive success of corals and the ability to regenerate after disturbance. A number of studies also highlight the importance of other factors in controlling algae proliferation in coral reefs, especially herbivory (Szmant, 2002).

The observed phase shift of coral reefs due to nutrient enrichment is a classic ecological problem of bottom-up versus top-down controls (Littler et al., 2006). Bottom-up control refers to the effects of nutrient enrichment on the base of the food web while top-down is control of the food web by the higher trophic levels, such as herbivores. One study showed that the level of herbivory had a much greater impact on the density and growth of seaweed recruits than did nutrient enrichment (Diaz-Pulido & McCook, 2003). Likewise, another study found herbivory to be a major factor in the colonization and survival of CCA communities in competition with macroalgae (Belliveau & Paul, 2002).

Littler and Littler (1984) proposed a conceptual model relating nutrient variability and herbivory to the type of benthic community (Figure 2.8). The model states that under pristine conditions, where grazing is intense and nutrients are relatively unavailable, corals will dominate the reef. If nutrient availability increases but grazing remains intense then coralline and encrusting algae, which are capable of reef building, will dominate. If herbivory is restricted, algal turf will dominate with low nutrient availability and fleshy macro-algae with high nutrient availability.

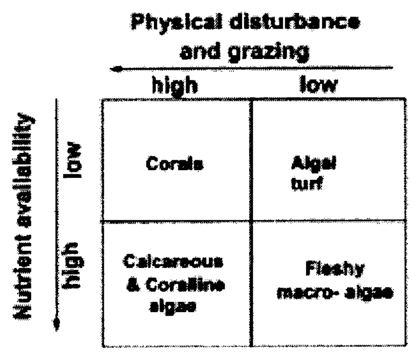

Figure 2.8: Conceptual model of dominant benthic community in relation to nutrient availability and herbivory in coral reef ecosystems
(Littler & Littler, 1984)

Although some of the evidence discussed above suggests that nitrogen enrichment may not always be detrimental to coral reefs, the potential impacts on water quality and coral health still warrant investigation. In general, as a limiting nutrient becomes increasingly available in an aquatic ecosystem, it will inevitably lead to poor water quality and eutrophication. Whether degradation occurs gradually or only after some threshold nutrient concentration is reached is not well known and still a popular area of research. In the coastal bays around St. John, nitrogen availability may not have reached high enough levels to cause noticeable changes in ecosystem health. But as more housing developments are constructed, nitrogen will become more available and may eventually lead to serious impacts on the health of coral reefs.

2.2.2.7 Coral health around St. John

Coral ecosystems all around the world are experiencing significant declines, and the Caribbean is no exception. In the U.S. Virgin Islands, living coral cover less than 20% of the bottom of most reefs, whereas twenty-five years ago, living coral covered more than 40% (Jeffrey et al., 2005; Ray, 2007). Ninety percent of Elkhorn corals, an important reef building coral, have been killed by disease or hurricanes in the Virgin Islands. In fact, diseases are found in coral as deep as 90 ft. Evidence of coral decline can be seen in the fish populations, where fish are not only dwindling in numbers, but also in size. Coral bleaching has been observed in the USVI since 1987 (Boulon, 2007). During 1998-1999, the entire Caribbean experienced very high surface temperatures. Not surprisingly, the high temperatures in 1998 were coincidental with a large bleaching event. Bleaching continues to be a major threat to coral in the Virgin Islands. During the end of 2005 through the beginning of 2006, a three-month seawater warming event in the Caribbean led to severe bleaching. While local scientists are still quantifying the damage, early estimates indicate the loss of up to 50-80% of living coral cover on St. John, from this event alone (Boulon, 2007). It is clear that the increased stress over the past decades has caused a marked decline in coral cover and coral health on St. John and in the Caribbean at large.

2.3 Nitrogen

Nitrogen is an important element for organisms. It is a primary element found in organic compounds, and is consumed by plants and microorganisms. The benefit of nitrogen as a nutrient has been exploited in agriculture and is necessary for the growth of crops, but increased nitrogen loading of water bodies can cause eutrophication, as explained in Section 2.2.2.6. The following sections describe the nitrogen cycle and nitrogen loading.

2.3.1 Nitrogen Cycle

The nitrogen cycle shows the different forms nitrogen can take within the environment, how it is changed from one state to another, and how it is transported from one location to another. The nitrogen cycle is shown in Figure 2.9.

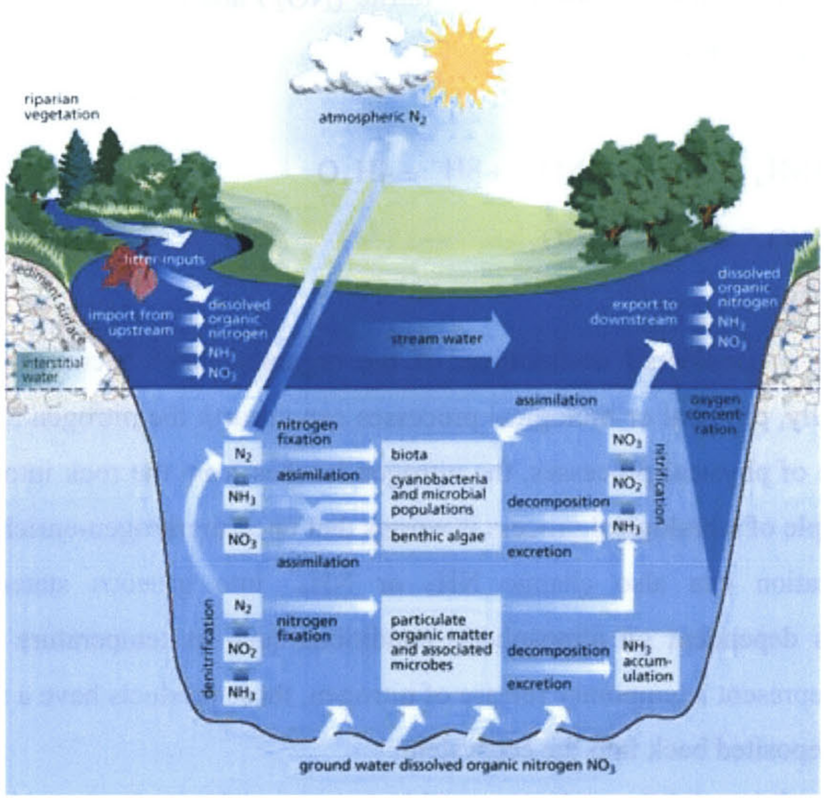

Figure 2.9: The nitrogen cycle
Source: (O'Keefe et al., 2002)

Nitrogen is commonly dissolved in water in the form of nitrate, or NO_3^-. This form is highly mobile and easily absorbed by organics (Jarvis, 1999). It can be naturally introduced into a system through transport by either surface flows or groundwater flows, or by human processes through excess fertilization, sewer effluent, high-production farm effluent, or effluent from chemical facilities. Runoff from nitrogen-rich sites can also transport it from terrestrial sources to the water in a process called "leaching." The primary absorbers of NO_3^- are plants, algae, and phytoplankton which use nitrogen to build amino compounds ($NH_2 - R$) for their organic structure. The nitrogen remains within the organism until it dies (Davis & Masten, 2004).

As an organism decomposes, nitrogen is released back into the system in the form of ammonia (NH_3). At the pH of most natural water, the ammonia captures hydrogen to form ammonium (NH_4^+) which can then be processed by nitrifying bacteria back into NO_3^- (Davis & Masten, 2004). Ammonium is generally immobile and can be used to trap nitrogen as long as there are no organic processes to convert it to highly mobile NO_3^-. Plants can also use ammonium in organic absorption (Jarvis, 1999). This process is called nitrification and it involves converting the ammonium ion into nitrite (NO_2^-) and then converting the nitrite into nitrate. The process is shown below:

$$4NH_4^+ + 6O_2 \rightarrow 4NO_2^- + 8H^+ + 4H_2O \qquad \text{(Equation. 2.1)}$$

$$4NO_2^- + 2O_2 \rightarrow 4NO_3^- \qquad \text{(Equation. 2.2)}$$

Nitrogen is considered immobilized if the organic matter becomes is buried (Jarvis, 1999). Eventually, physical or biological processes can unearth the nitrogen and return it to the system. In case of physical processes, the nitrogen leaches from the rock into the soil or water body. An example of a biological process is worms that unearth nitrogen-enriched minerals.

Volatilization can also change NH_3 or NH_4^+ into gaseous states (Jarvis, 1999). Volatilization is dependent on atmospheric conditions such as temperature and wind speed. Although they represent a temporary release of nitrogen, these products have a short half-life and eventually are deposited back into the ecosystem.

Equations 2.1 and 2.2 require an aerobic (oxygen-rich) environment to process. If the oxygen is not replenished, the oxygen can be fully exhausted, resulting in an anoxic (oxygen-poor) environment (Davis & Masten, 2004). In such an environment, nitrate can be processed with organic carbon by bacteria to produce nitrogen gas, carbon dioxide, and water. The nitrogen is released into the air and becomes removed from the system. This process is called denitrification.

Nitrogen gas can be consumed by photosynthetic bacteria called cyanobacteria and returned to organic nitrogen (Davis & Masten, 2004). Other organisms have been known to process nitrogen gas, especially lichens which form a symbiotic relationship with cyanobacteria to produce energy. This process is called nitrogen-fixation and the process is shown below:

$$N_2 + 8e^- + 8H^+ + ATP \rightarrow 2NH_3 + H_2 + ADP + P_{inorganic} \qquad \text{(Equation. 2.3)}$$

2.3.2 Nitrogen Loading

One of the objectives of this project is to evaluate the nitrogen loading that is occurring to the coral reefs on the Virgin Islands. Different methods have been developed to determine nitrogen loading rates, but almost all methods are based on quantifying the rates of nitrogen production, transport, and accumulation within a watershed. The following section discusses three studies to determine the extent of nitrogen loading within a watershed. The first study estimated the amount of nitrogen entering coral reefs at various locations through submarine groundwater discharges. The second study documents the Waquoit Bay Land Margin Ecosystem Research project's evaluation of nitrogen loading. The third study compares two methods of evaluating nitrogen loading on the coral reefs at Ishigaki Island, southwest of Japan.

2.3.2.1 Submarine groundwater discharge

The purpose of the first study was to estimate the amount of nitrogen being released into the coral reef through groundwater discharges on the ocean bottom (Paytan et al., 2006). Generally, groundwater is fresh until it reaches the ocean where it mixes with the saline ocean water. The release of groundwater into ocean water is called submarine groundwater discharge (SGD) Although many studies have been performed to calculate the amount of nitrogen loading to the coral reefs from surface water sources, little has been done to evaluate nitrogen loading from SGD due to the difficulty in measuring nutrients beneath the water (Paytan et al., 2006).

The purpose of the Paytan study was to measure the amount of total inorganic nitrogen (TIN) being released to coral reefs at specific sites through water sampling. Radium (Ra) isotopes were used as a tracer to determine the amount of groundwater entering the ocean (Paytan et al., 2006). Samples were obtained at various locations on the Florida Keys, the Gulf of Aquaba, Puako, Hawaii, Kaloko, Hawaii, Kahana, Maui, and Mauritius. Water analyses were performed on the samples to measure salinity, Ra activity, and nutrient concentration. It was determined by comparing nutrient concentrations and Ra activity that a substantial amount of nutrients was being brought into the coral reefs through SGD. It was estimated that around 60% of all nutrients within the coral reefs come from ground water sources.

2.3.2.2 Waquoit Bay Land Margin Ecosystem Research project

The Waquoit Bay Land Margin Ecosystem Research (WBLMER) project is involved in estimating and modeling the water quality within Waquoit Bay. The project was motivated by the bay becoming increasingly eutrophied and thus a threat to the ecosystem health. Because nitrogen is usually the limiting nutrient in estuaries, a model was developed to estimate the amount of nitrogen loading within the watersheds (Valiela et al., 1997).

The nitrogen loading model, called the WBLMER model, was designed to estimate nitrogen within the Waquoit estuary by evaluating the nitrogen generation and transportation within the sub-watersheds of the region, approximating the amount of nitrogen being deposited from the atmosphere, and predicting the amount of degradation or absorption of nitrogen by organic processes (Valiela et al., 1997).

To estimate the amount of nitrogen within the watershed, the Waquoit estuary watershed was divided into sub-watersheds and nitrogen loading sources were compiled within each one. The nitrogen loading sources were divided into two categories; point sources and non-point sources (Valiela et al., 1997). Point sources are locations where there is a defined point of effluent such as septic systems. The rate of effluent discharge and concentration of nutrients is used to calculate the amount of contamination the point source contributes to the system. Housing units counted from aerial photographs and the average number of people from each household is estimated through census data. These values are used to calculate the amount of effluent produced from each house. Non-point sources are large areas that can be characterized by a single attribute, such as a soil group, a crop grown on a specific area, or how the land is developed. Nutrient release is estimated to be the average nutrient release of the given area. An average value of nutrient release is estimated for the entire area based on its size and attribute.

The model then simulates nitrogen transport. Nitrogen transport is modeled for two systems: surface-water runoff and groundwater infiltration. Calculating the transport of nutrients is essential not only as an indicator of where the water will travel but also how long it will take to reach the receiving waters. This is because nutrient loss through soils increases within the soil due to nutrient absorption by organisms and retention within the soils. A hydrological analysis of the watershed surface is used to determine where the surface water will travel and the retention times for major ponds. Groundwater flow is calculated using hydrologic flow and particle-tracking models (MODFLOW). MODPATH is also used to estimate the amount of groundwater contributing to the ponds (Valiela et al., 1997).

By compiling nitrogen accumulation and release rates, and nitrogen losses through transport, the entire watershed can be modeled to estimate the nitrogen loading rate for the receiving waters (Valiela et al., 1997). For the Waquoit estuary, nitrogen generation was modeled to be 115,000 kg N/yr. Due to nitrogen absorption within the system, only 20% actually reaches the estuary, for a total of 23,000 kg N/yr nitrogen loading rate. In order to estimate how precise the model is at predicting nitrogen loading, the model was repeated 2000 times using different climate data and small variations of different watershed parameters. Compared to the actual nitrogen concentrations within the water, the estimates were within 37% of the mean loading rate. The report concludes that although inaccurate, continual research and supporting field data should be used to improve the model's accuracy. Valiela also acknowledges that considerable research must be done before highly accurate models are capable of simulating environments.

2.3.2.3 Groundwater nitrogen discharge into coral reefs at Ishigaki Island, southwest of Japan

The purpose of the third study was to compare two methods of estimating groundwater nitrogen discharge into the coral reefs at Ishigaki Island. Two coral reefs were observed; the Shiraho estuary and the Kabira estuary. The first method involves estimating the dissolved inorganic nitrogen (DIN) using the concentration of DIN in groundwater taken close to the shoreline and multiplying the value by the total groundwater flow into the receiving water (Umezawa et al., 2002). An equation of the model is shown below:

$$N_{gi} = P \times A \times R \times [DIN] \qquad \text{(Equation 2.4)}$$

where N_{gi} is the nitrogen input to the reefs through groundwater (kg N/year), P is the annual precipitation (mm/year), A is the area of the watershed (km^2), [DIN] is the DIN concentration in the groundwater (μM), and R is the groundwater discharge to precipitation ratio. Eight well sites were used for this method (Umezawa et al., 2002).

The second method involved estimating the amount of nitrogen loading through the land use areas around the bays. This method used census data, land usage, and effluent concentrations to estimate the amount of nitrogen being released into the bays (Umezawa et al., 2002). The method assumed that nitrogen only came from two sources: fertilizer and sewer effluent systems. As a result, the model assumes that human sources are the primary nitrogen sources and does not take into account non-human sources. The equation for the model is shown below:

$$N_{gi} = F + W \qquad \text{(Equation 2.5)}$$

where F is the amount of nitrogen derived form fertilizer applied to agricultural lands and pastures (kg N/year) and W is the amount of nitrogen reaching the groundwater through wastewater effluent (kg N/year) (Umezawa et al., 2002).

While both methods attempt to calculate the same value, they do so by taking different factors into account and making different assumptions. The first method uses actual data for nitrogen concentration and rainfall to calculate the flow. It is relatively simple because it uses water quality of the groundwater flow that is relatively close to the receiving waters. Difficulty can arise if the watershed that has a large seepage face or if it is difficult to retrieve groundwater samples. Alternatively, the second method uses only census data to make empirical assumptions as to the nitrogen's origin and its method of transportation. No site testing is needed for this method but aerial maps of the watershed are required to obtain the number of point sources (Umezawa et al., 2002). Neither method takes into account nitrogen loss during transportation, but it is assumed that little nitrogen losses would occur due to the small watershed size.

The first method computed values of 35-40 and 3.5-18 kg N/year for Shiraho Bay and Kabira Bay respectively. The second method calculated values of 80-115 and 14-21 kg N/year for Shiraho Bay and Kabira Bay respectively (Umezawa et al., 2002). Both methods produced values that were within a factor of ten from each other, although method II had slightly higher loading rates compared to method I. This could be because method II does not take into account nitrogen losses and overestimates the nitrogen loading amount (Umezawa et al., 2002). Both methods show the difficulty in accurately predicting natural processes but can be used to estimate the approximate amount of loading.

2.4 Experimental Design

The goal of the larger project, which is the context of this study, was to determine the effect of development on St. John on coral health, specifically sediment and nitrogen loading. To do this, we predicted coral health and sediment and nitrogen loading rates in multiple bays, including those with few developments, and those that are heavily developed. A comparison of coral health in the two types of bays gave us an indication as to whether development plays a local role in coral health; for example, if a developed bay has coral that are significantly less healthy, or has significantly less coral, one could say that development may have a negative effect on coral. Likewise, if the two types of bays have no significant difference in coral health, one cannot say that development affects coral, at least at a local level. A comparison of sedimentation and nitrogen loading rates in the bays gave us an indication as to whether these loading rates play a role in coral degradation.

Another potentially important factor that may differentiate coral health in different bays is watershed size. Compared with a small watershed, a large watershed will produce more runoff and carry with it more sediments and nutrients from the surface.

We focused our study on four bays on St. John: one developed and one undeveloped with small watersheds, and one developed and one undeveloped with large watersheds. This allowed us to examine the relationships between development on the island and watershed size with the health of coral reefs in the bays. We chose four specific bays based on the level of development, presence of coral, and watershed size. Out of the bays with small watersheds, we investigated the undeveloped Leinster Bay and the developed Round Bay. Out of the bays with large watersheds, we investigated the undeveloped Reef Bay, and the developed Fish Bay, one of the most developed watersheds on St. John. Figure 2.10 shows the location of these four bays, and the sizes of each watershed.

Figure 2.10: Aerial photograph with site locations.

2.5 Objective

The purpose of this thesis is to quantify the amount of nitrogen loading occurring within specific bays on St. John, and to determine how this is affected by recent development. The initial hypothesis is that there is significant nitrogen loading caused by development on the island and that in the last fifteen years there has been an increase in nitrogen loading that is related to the increase in development. The following sections describe the methodology used to estimate the effect of development on nitrogen loading, the results from the methodology, and a discussion of the implications of the results.

3 METHODOLOGY

The following sections describe the four methods used to evaluate the impact of development to nitrogen loading within the bays. The four aspects of the study include 1) field research, 2) GIS-based analysis, 3) a nitrogen loading model, and 4) historical data analysis. All were used to evaluate the relationship between developments and nitrogen loading of the bays.

3.1 Field Research

The first method involved determining the amount of nitrogen within the bays and identifying whether there is a relationship between nitrogen and the development within each watershed. To do this required that water samples be taken from the bays and measured for nitrogen. The observed nitrogen concentrations would also be used to help calibrate the nitrogen loading model. The following methods were based on work done by Valiela et al. (2000) to ascertain the accuracy of the Waquoit Bay Nitrogen Loading Model.

As stated in Section 2.4, Experimental Design, four bays were evaluated with field testing to determine the impact of development on coral health. Water samples would be taken from all four bays at various locations within the bays, with the purpose of determining whether there were substantial differences in nitrogen concentrations between the bays. Samples were generally taken at close proximity to the coral reefs of concern. Coordinates of each site were recorded using a Global Positioning System (GPS) unit.

Groundwater samples were also to be obtained at various points within the watersheds of each bay and also at locations close to the shoreline. These values would be used to calculate the percent of denitrification within the aquifer. Unfortunately, groundwater samples were unobtainable with the equipment we had because the aquifer is fractured bedrock.

Water samples were measured using the Hach DR/2010 Portable Datalogging Spectrophotometer. An image of the spectrophotometer is shown in Figure 3.1. The tests performed were the Nitrate HR Cadmium Reduction Method (Hach Method Number 355), the Nitrite LR Diazotization Method (371), and the Ammonia Salicylate Method (385). The nitrate cadmium reduction method uses packets of cadmium that react with the nitrate to form an amber-colored salt that allows the spectrophotometer to measure nitrate concentration. It has a range of 0 to 30 mg/L and detects within an accuracy of ±0.8 mg/L. The nitrite diazotization method uses sulfanilic acid to precipitate a pink salt. This method has a range of 0 to 0.300 mg/L and has an accuracy of ±0.0011 mg/L. The ammonia salicylate method uses a packet of chlorine and salicylate and one packet of sodium nitroprusside catalyst to form a green-colored solution. The method has a range of 0 – 0.50 mg/L and an accuracy of ±0.015 mg/L. One issue with the ammonia salicylate method is that it is used to find the difference in ammonia concentration between two samples, and assumes the blank sample is deionized water with no ammonia. For practical purposes, demineralized water was used instead. As a result, all ammonia samples are comparisons between the concentration of ammonia in the sample with ammonia in the demineralized water. Samples of demineralized water were brought back and compared with deionized water and found to have no difference in ammonia concentrations. Detailed instructions can be found in the DR/2010 Spectrophotometer Procedures Manual (Hach Company, 2000). Calibration curves were developed using standard solutions to ensure accuracy of the tests. The standard solutions of nitrate, nitrite and ammonia were diluted using deionized water to predetermined concentrations and tested using the spectrophotometer. The values were then averaged and plotted alongside the known concentrations to develop an equation to determine the exact nitrogen concentrations. The developed calibration curves for the nitrate, nitrite, and ammonia tests are found in Appendix A, Figure A.1, Figure A.2, Figure A.3 respectively.

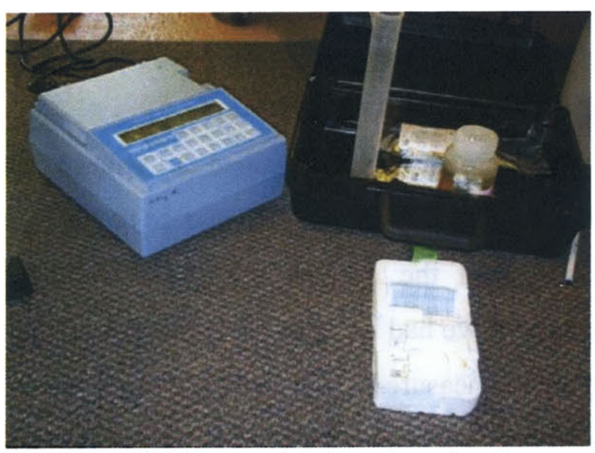

Figure 3.1: Hach DR/2010 Portable Datalogging Spectrophotometer

3.2 Geographic Information System

A geographic information system (GIS) was assembled using ArcGIS Version 9.2 (Environmental Systems Research Institute, Inc. (ESRI), 2007a) to obtain the characteristics of the bays and watersheds, and also to quantify the level of development within each bay. A high resolution aerial photograph of St. John was obtained from the Center for Coastal Monitoring and Assessment (2007) and used as a base map for the GIS (Appendix B, Figure B.1) (Center for Coastal Monitoring and Assessment, 2007). The following sections describe the methods for identification of the bays on the island, quantifying the bay dimensions, delineating the watersheds of each bay, and estimating the level of development within each of the bays.

3.2.1 Bay Identification

Before being able to collect any spatial information, each bay around the island needed to be delineated and identified. A shapefile was created to store a set of polygons, which defined the extents of all the bays around the island. Bays were identified by their geometries being enclosed by the shoreline on all sides except one which opened to the ocean. This process was somewhat subjective since some bays could be merged to form one larger bay or subdivided into multiple smaller bays. When defining the extent of a bay, the surface area and expected watershed size were taken into account in order to minimize the overall range in bay and watershed sizes.

3.2.2 Bay Dimensions

The average depth of each bay was calculated using a digital bathymetric chart obtained from the NOAA Electronic Navigation Charts (ENC) Direct to GIS internet utility (National Oceanic and Atmospheric Administration, 2006). ENCs are digitized versions of the NOAA navigational charts which provide important information for maritime navigation such as water depths and the locations of buoys and hazards. The Direct to GIS utility exports a geodatabase containing all the ENC information separated into individual layers for a specified region—the region around St. John spanned ENCs #25647 and #25641. The bathymetric chart consisted of a series of polygons that were assigned a maximum depth and a minimum depth which corresponded to the depths at mean lower low water of the far-shore and near-shore boundaries, respectively (Appendix B, Figure B.2-A) By finding the intersection of the bathymetric chart and the bay delineations, a series of individual bathymetric charts were produced for each bay (Appendix B, Figure B.2-B).

Using these individual bathymetric charts, the areas of the depth polygons within each bay were calculated. The average depth of a polygon was approximated by the arithmetic average of its maximum and minimum depths. The total volume of water represented by a depth polygon was calculated as the product of its average depth and its area. The total bay volume is then the sum of all the depth polygon volumes within the bay, and the average depth of the entire bay is the total volume divided by the surface area.

3.2.3 Watershed Delineation

The watershed of each bay on St. John was delineated using the ArcHydro toolpack for ArcGIS (Environmental Systems Research Institute, Inc. (ESRI), 2007b). To conduct this analysis, a Digital Elevation Model (DEM) with 30 meter resolution (1:24,000 scale) was obtained from the National Elevation Dataset (NED) using the USGS Seamless Data Distribution System (United States Geological Survey, 2004) (Appendix B, Figure B.3). In order to delineate the watersheds, the basic hydrologic behaviors such as flow directions, flow accumulations, drainage channels, and catchment areas were calculated for the entire island using ArcHydro. Once these calculations were complete, the watershed delineation tool was used to find drainage area of each bay.

3.2.4 Roads and Developments

To model the amount of nitrogen and sediment delivered to each bay, the number of developments and total length of roads were needed for each watershed. Using the aerial photograph, every visible house and development on the island was marked by a point and every road by a line. By spatially joining these features to the watershed layer, the number of developments and total length of roads within each watershed could be calculated in ArcGIS.

3.3 Nitrogen Loading Model

In addition to the field research, a nitrogen fate and transport model was used to estimate the amount of nitrogen loading within each of the bays. By predicting the amount of nitrogen loading occurring within the bays and correlating it to the level of development within each bay, one can quantify the impact of nitrogen releases from developments on the bays.

The Nitrogen Loading Model (NLM) is based on the work of Ivan Valiela (Valiela et al., 1997) and his research of nitrogen loading rates of Waquoit Bay on Cape Cod, Massachusetts. Initially called the Waquoit Bay Land Margin Ecosystem Research Nitrogen Loading Model, the model first calculates the amount of nitrogen input from atmospheric deposition, septic tanks and cesspools, and fertilizer. It then estimates the amount of loading into the receiving estuary by simulating the media the nitrogen must travel through and the losses that occur as the nitrogen passes through each medium. The associated losses are derived from literature and also result from field research. A summary of the model as well as field researched conducted with the Waquoit Bay Land Margin Ecosystem Research Nitrogen Loading Model is in Section 2.3.2.2. The NLM was chosen for our use on St. John because of its flexibility with different parameters and because the model differentiates nitrogen from natural sources and human sources. The model for this project is called the St. John Nitrogen Loading Model (SJNLM).

The following sections discuss how the NLM calculates nitrogen loading and also the parameters used for the USVI model. The first section discusses the modeling of nitrogen sources, and the next section discusses nitrogen losses through different media. A visual representation of the model is shown in Figure 3.2. The model includes sources of nitrogen (shown in green boxes) and nitrogen sinks (shown in red boxes). A table showing an overview of the nitrogen transport within the model and the respective values used is shown in Table 3.1.

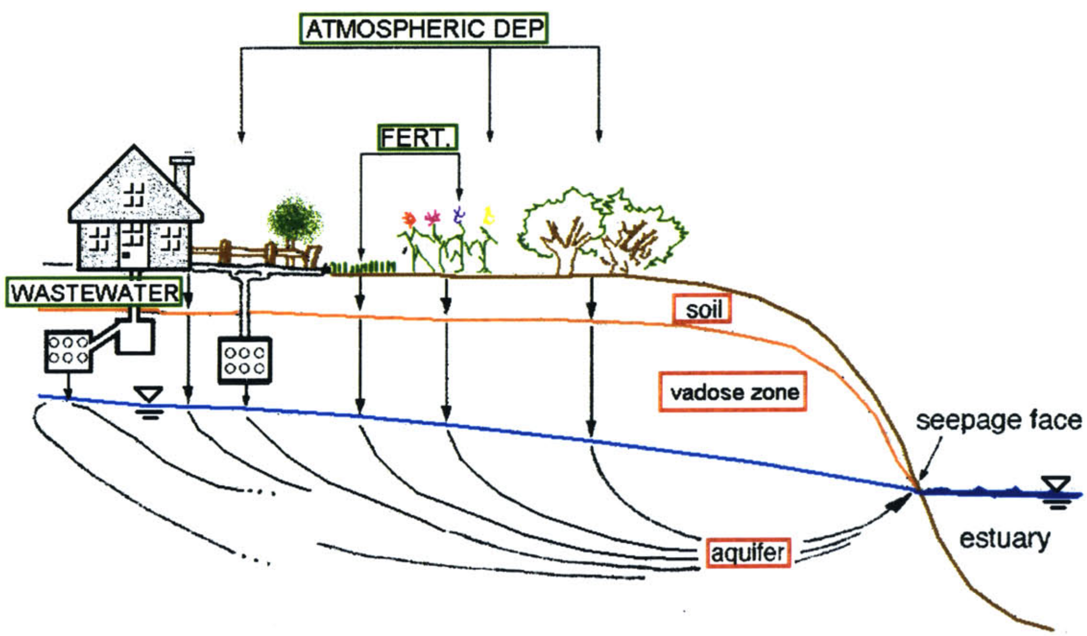

Figure 3.2: Visual representation of the Nitrogen Loading Model
Source: (Valiela et al., 1997)

Table 3.1: Summary of sources and sinks for the Saint John Nitrogen Loading Model

Sources	**Value**	**Unit**
Annual wet and dry deposition of nitrogen	2	kg of N per ha per year
Average N released per person	4.82	kg per person per year
Sinks	**Value**	**Unit**
N uptake on vegetated soils	68%	percent of deposition retained
N uptake within vadose zone	38%	percent of deposition retained
Reduction in N within septic tanks	6%	percent of N retained
Reduction of N within leaching field	35%	percent of N retained
Reduction of N within effluent plume	34%	percent of N retained
Reduction of N within aquifer	0 - 35%	percent of N retained

3.3.1 Nitrogen Sources

The nitrogen model first quantifies the nitrogen sources within each bay (Valiela et al., 1997). The NLM predicts three sources of nitrogen: atmospheric deposition, fertilizer, and septic systems. Atmospheric deposition refers to nitrogen that arrives into the watershed through wet or dry deposition. Wet atmospheric deposition is nitrogen that enters the estuary as ammonium and nitrate dissolved in raindrops. Values for wet deposition are determined by testing nitrogen concentrations of collected rainwater. Dry deposition is the absorption of NO_X gases and ammonia within the air into vegetation. Little information is known about the rates of dry deposition (Valiela et al., 1997) but various studies have indicated that annual dry deposition is approximately the same magnitude as wet deposition (Valiela et al., 1997). Therefore, when dry deposition rates are unknown, the total amount of atmospheric nitrogen deposition is taken as the annual wet nitrogen deposition multiplied by two.

3.3.1.1 Atmospheric deposition sources

The wet atmospheric deposition of nitrogen for St. John was obtained from the National Atmospheric Deposition Program (National Park Service, 2006). An atmosphere monitoring station is located on St. John and is maintained by the Virgin Islands National Park Service. A picture of the sampling apparatuses is shown in Figure 3.3. For 2005, the annual wet deposition for nitrogen was 3.07 kg/ha of NO_3^- and 0.44 kg/ha of NH_4. Summing both values and converting the concentrations to nitrogen, the annual wet deposition of nitrogen is 1.06 kg of N per ha. Multiplied by two to account for dry deposition, the annual atmospheric deposition of nitrogen is approximately 2 kg of N per ha.

Figure 3.3: Atmospheric sampling station on St. John
Source: (National Park Service, 2006)

3.3.1.2 Fertilizer sources

Fertilizers are a significant source of nitrogen in many watersheds. The model divides fertilizer usage into turf use and commercial horticulture use (Valiela et al., 1997). Turf has fertilizer applied on a continual basis to ensure optimal conditions when the turf is in use, while horticultural usage of fertilizer varies depending on the crops grown and the growing seasons. For horticultural fertilizer usage, it is recommended by Valiela that nitrogen release from the plants be tested. Because the majority of St. John is a national park, fertilizer use is kept to a minimum. It is possible that fertilizer application occurs within the resorts but those resorts are not located on the bays studied. Therefore, the implementation of the SJNLM ignores fertilizer as a potential source of nitrogen.

Animal sources are not taken into consideration because they consume plants that obtain their nitrogen from the atmosphere. Therefore, the model assumes that the nitrogen source from livestock has already been quantified in the atmospheric deposition result and is not an actual source (Valiela et al., 1997). Other animal sources such as pets that consume imported food or waterfowl that migrate to the island are assumed to contribute a negligible amount of nitrogen to the island.

3.3.1.3 Human sources

Humans are the third source of nitrogen computed for the NLM. Humans contribute nitrogen loading through the import of food from sources off the island that are consumed and eventually deposited. The majority of nitrogen from human sources enters the watershed through wastewater facilities, septic tanks, and cesspools.

The amount of nitrogen loading from humans was quantified using the number of houses found within each watershed. There is one wastewater treatment facility on the island that serves the majority of Cruz Bay but it discharges one mile offshore, far away from the observed bays. Therefore, this project focuses on nitrogen loading through septic tanks and cesspools. Aerial photographs were used to count all the developments within each watershed (Center for Coastal Monitoring and Assessment, 2007). County data from the 2000 census was used to determine the average number of people per household and the percent of the houses that had septic systems or cesspools (U.S. Census Bureau, 2002). The county data was correlated to the watershed to obtain region-specific values. For example, if 30% of the houses within a watershed were in one county and the other 70% was within another county, a weighted value of 30% of the first county and 70% of the second county was used for number of people per household and percent of houses with septic systems. The number of houses with septic systems or cesspools was multiplied by the average household population to determine the number of people within the watershed. This number was multiplied by the average annual nitrogen release per person to calculate the total amount of nitrogen released by people. Valiela et al. (1997) uses 4.8 kg of N per person per year as the amount of nitrogen an average person would produce per year. This value is not specific to Waquoit Bay, and therefore the SJNLM uses the same value.

3.3.1.4 Nitrogen losses

Once the sources are calculated, the NLM estimates the nitrogen losses within the watershed based on the different paths the nitrogen can take to reach the estuary. It does so by summing the amount of nitrogen that enters a given zone and multiplying it by the fraction of nitrogen that is allowed to pass through. The four major media where nitrogen loss occurs are the topsoil, the vadose zone, the aquifer, and within fresh water bodies (Valiela et al., 1997). While many of Valiela's loss coefficients were used, some values were altered to reflect differences in type of climate and vegetation. The following sections discuss losses from land coverage, losses within the vadose zone and aquifer, and losses for septic tanks and cesspools.

3.3.1.5 Land coverage losses

The NLM assumes that atmospheric deposition of nitrogen is constant throughout the entire watershed but that losses occur depending on the land cover. The four land covers used in the NLM are naturally vegetated land; cultivated land; roofs and driveways; and roads, runways, and commercial areas (Valiela et al., 2002). ArcGIS was used to count the number of developments within each watershed shown on the aerial photograph. The program was then used to find the average area of the developments and the average length of driveway of each house. The lengths of the roads within each watershed were then measured and the total length multiplied by the average paved road width of 3.7 m. This value was approximated through observation of the roads. There were unpaved roads on the island but because the fraction was small and difficult to visualize on the aerial photograph, they are counted as paved roads. Unaccounted impervious surface area was then estimated through visual inspection. Because the island is mostly vegetation, most of the bays had no unaccounted impervious area.

Losses of nitrogen deposited on naturally vegetated lands are dependent on the nitrogen uptake of plants within the watershed. Kaye et al. (2002) researched the uptake of nitrogen by three different species of trees (Eucalyptus, Casuarina, and Leuceana) on the northern coast of Puerto Rico. They observed that after seven years, 62 to 75% of the nitrogen added to the trees remained non-labile on the soil surface. We used the median value (68%) as the percent retained on naturally vegetated soil in our model. This is close to the original NLM value of 65% given by Valiela et al. (1997). Cultivated land is assumed to be the same percent loss as in the NLM (62%). Runoff from roofs and driveways is assumed to flow onto the lawn turf and has the same nitrogen loss as cultivated land. Roads are assumed to flow through no vegetation and seep directly into the vadose zone through catch basins and therefore have no loss of nitrogen.

3.3.1.6 Vadose zone and aquifer losses

There has been little research on nitrogen losses within the vadose zone and within aquifers (Valiela et al., 1997). Nitrogen losses within the vadose zone are attributed to absorption through roots or consumption by microorganisms. The Waquoit Bay NLM used nitrogen losses for agricultural fields above unsaturated sands (61% nitrogen lost). For the SJNLM, the nitrogen loss within the vadose zone was obtained from a study on nitrogen retention of Coto clay, a type of soil found in Puerto Rico (Areclay, 2005). The study analyzed nitrogen concentrations within the Coto clay of the region at different depths for two years. The average proportion of total nitrogen that percolates to the groundwater from the surface is 20%. To obtain the percent of nitrogen that is lost within the vadose zone, the percolation percent from Areclay (2005) (20%) was divided by the vegetation uptake derived from Kaye et al. (2002) (32%) to obtain 62% as the percent of entering nitrogen that passes through the vadose zone, or 38% as the percent of total nitrogen that is retained.

Compared to losses within the vadose zone, there is even less information about nitrogen losses through aquifers. Aquifer denitrification is considered "one of the largest unknowns in the whole topic of nitrogen loading" (Valiela et al., 1997). Denitrification usually occurs under anoxic conditions through consumption of degradable organic matter by microorganisms. It was previously assumed that the lack of anoxic conditions and organic matter would prevent denitrification from occurring. In contrast to what was predicted, recent studies have shown that denitrification does occur within aquifers, presumably through microorganisms or reactions with minerals. Valiela et al. (2002) recommend that water samples be taken at different locations within the watershed and at the aquifer seepage face within the estuary to estimate nitrogen losses within the vadose zone and aquifer. We planned to obtain groundwater samples while on the USVI but, as previously mentioned in the field research section, it was impossible to obtain samples because the mini-piezometer could not penetrate the fractured volcanic rock of the aquifer. The Waquoit Bay NLM uses the average of multiple sources to obtain a value of 35% as the nitrogen loss occurring within its aquifer. A major difference between the Waquoit Bay model and the St. John model is that the Waquoit Bay model assumes a sandy aquifer while St. John has an aquifer composed of fractured volcanic rock (Miller et al., 1997). Due to the composition of the aquifer and the distance the groundwater needs to travel to reach the seepage face, it is possible that nitrogen losses are much less than those predicted for Waquoit Bay, and possibly non-existent. Therefore, a range of nitrogen loss values from 0% to 35% for the aquifer were used for the SJNLM. This range represents the uncertainty of the model at predicting the nitrogen loss within the aquifer.

3.3.1.7 Septic tank and cesspool losses

The NLM estimates three different components of nitrogen loss for the discharge of septic tanks: loss within the septic tank, loss within the leaching field, and loss during the dispersal of the plume (Valiela et al., 1997). These losses within each part of the septic tank were obtained through comparison of the nitrogen concentrations at various points within the septic systems and in the effluent. Valiela (1997) estimates that 9% of the nitrogen is lost within the septic tank, 35% is lost within the leaching field, and 34% is lost as the plume disperse. The same values are used in the SJNLM. The nitrogen losses within the plume take into account vadose zone nitrogen losses and therefore are not multiplied by that value.

In the Waquoit Bay NLM, cesspools are different from septic tanks in that they do not benefit from the losses through leaching fields (Valiela et al., 1997). Although cesspools were a traditional method for treating wastewater, they are now illegal in Massachusetts for domestic wastewater supplies. The retrieved census data for St. John did not differentiate between homes with septic tanks and homes with cesspools. Therefore, cesspools are ignored in this model.

Usually, nitrogen from the plume travels directly to the aquifer, and losses from the aquifer are taken into account. However, homes that are within 200 m of the estuary are assumed to not be far enough for nitrogen losses to occur within the aquifer. As a result, the total houses within each watershed are divided into homes within 200 m and homes further than 200 m from the estuary shoreline. Those homes within 200 m receive no nitrogen losses from the aquifer, while those further away receive aquifer nitrogen losses.

3.3.2 Model Predictions

The purpose of the SJNLM is to provide a method of quantifying nitrogen loading from development compared to nitrogen loading from natural sources. To help illustrate the impact of development on nitrogen loading, the model was run under three scenarios: if the island had no development, if the island had current levels of development, and if the island had the maximum level of development. Under no development conditions, the bays had no homes or roads, so all nitrogen came from atmospheric deposition. Current conditions were simulated using buildings and roads obtained from the aerial photograph (Center for Coastal Monitoring and Assessment, 2007). Maximum development conditions were simulated by assuming that the level of development was the same as the most developed watershed on St. John. The chosen bay was

Chocolate Hole Bay because it has the highest number of buildings per hectare. A building density of approximately 1.25 buildings per hectare was used to calculate the amount of buildings within each watershed. The impervious surface area was also assumed to be 5% and the percent of road area was assumed to be 2.8%. The area of the roofs for the total watershed came out to be 4.2%. The result is a total impervious surface area of 12% for each watershed. The number of buildings that were less than 200 m from the shoreline was assumed to be the same portion of the total number of buildings as currently. In cases where the watershed had no buildings or all the buildings were less than 200 m to the watershed, it was assumed that only half of the buildings were less than 200 m. From these values, the nitrogen loading from maximum development was obtained.

3.4 Historical Nitrogen Concentrations

Historical water quality data from many of the bays on St. John was obtained from the National Park Service (NPS) (McManus, 2006). The data was used to determine if there was a correlation between nitrogen concentrations and whether a bay's watershed is developed. Samples were taken approximately once a month, and up to three samples were taken in each bay on a given day. Water quality data used were the concentrations of nitrate, nitrite, and ammonia, but no organic nitrogen. All concentrations are reported in μM of N, and to get the total nitrogen all values were added together. The watersheds of the bays were classified by the NPS into undeveloped, partially developed, and developed watersheds. The classification of the bays was compared to average nitrogen concentrations and the rate of nitrogen change. The rate of nitrogen change was determined by plotting a linear regression versus time.

Although most of the nitrogen concentrations reported by the NPS were relatively low, a few large peaks in nitrogen concentration were observed in the time series, with up to seven times the background nitrogen concentration. The team suspected these peaks to be the result of major rain events that carried nitrogen from the soil into the bays. If this was true, then nitrogen concentrations from runoff are having a substantially larger impact on nitrogen loading than nitrogen releases from septic tanks, which are below the ground and do not contribute appreciably to runoff. This is based on the assumption that nitrogen from septic tanks is being released into the bays at a constant rate while runoff from large storms causes large nitrogen loads. Rainfall data was obtained from Rafe Boulon (Boulon, 2007), who took daily rainfall measurements at his house from 1983 to 2006. The rainfall data was then plotted with the nitrogen concentration data of Turner Bay because his house is located within the bay's watershed. One problem with the NPS nitrogen data is that samples were taken approximately once every three months. As a result, if a large storm produced substantial runoff, it could be several months before this nitrogen was measured in the bay. By that time, the nitrogen could have been used by the biota or flushed into the ocean. To compensate, each nitrogen sample was compared with the total rainfall that occurred within one week before the sample was taken. This allowed us to determine if an increased amount of rainfall produced higher nitrogen concentrations.

The detailed methods described in this chapter have been developed in order to understand the impact developments have on the nitrogen loading within each bay. The next chapter discusses the results obtained from the methodology.

4 RESULTS AND ANALYSIS

The previous chapter discusses the methodology used to assess the impact development has on nitrogen loading on the island of St. John, U.S. Virgin Islands. The four methods are a field study that involves comparing nitrogen concentrations within four bays on the island, using a geographical information system (GIS) to delineate the level of development within each watershed, using a nitrogen loading model to estimate the amount of nitrogen loading within the bays, and analyzing water quality data obtained from the National Park Service. This chapter documents the results of the field study, the GIS methodology, and the nitrogen loading model. The section also discusses the analysis performed on the National Park Service data and the correlations obtained from it.

4.1 Field Research Results

As stated earlier, four bays were sampled during the field research part of the project. Three water samples were analyzed within each bay except Fish Bay in which four samples were collected. GPS coordinates were obtained from all site locations except Fish Bay. Visual cues were used to estimate the location within Fish Bay which was then plotted using ArcGIS to obtain the coordinates. A map of the island with the locations of the sample sites is in Figure 4.1. A surface runoff sample was also tested to determine the presence of nitrogen within runoff. A summary table of the average concentrations within the bays is shown as Table 4.1 and a graph of the average concentrations within each bay is shown in Figure 4.2. A complete summary of the results is in Appendix C.

The observed nitrate concentrations are much larger than concentrations of nitrite and ammonia, and dominate total nitrogen concentrations. As mentioned in Section 3.1, the nitrate readings have an accuracy of ±0.8 mg/L. After calibration and converting to appropriate units, the accuracy translates to ±6.7 μM. All nitrate concentrations are below this value, and hence conclusions based on this data are somewhat inconclusive. Even so, the observed concentrations are within the range of the National Park Service data (Section 4.4) and as well as data reported by the National Oceanic and Atmospheric Administration (2002), which shows wintertime surface nitrate concentrations throughout the Gulf of Mexico are generally around 0.5 – 2.0 μM.

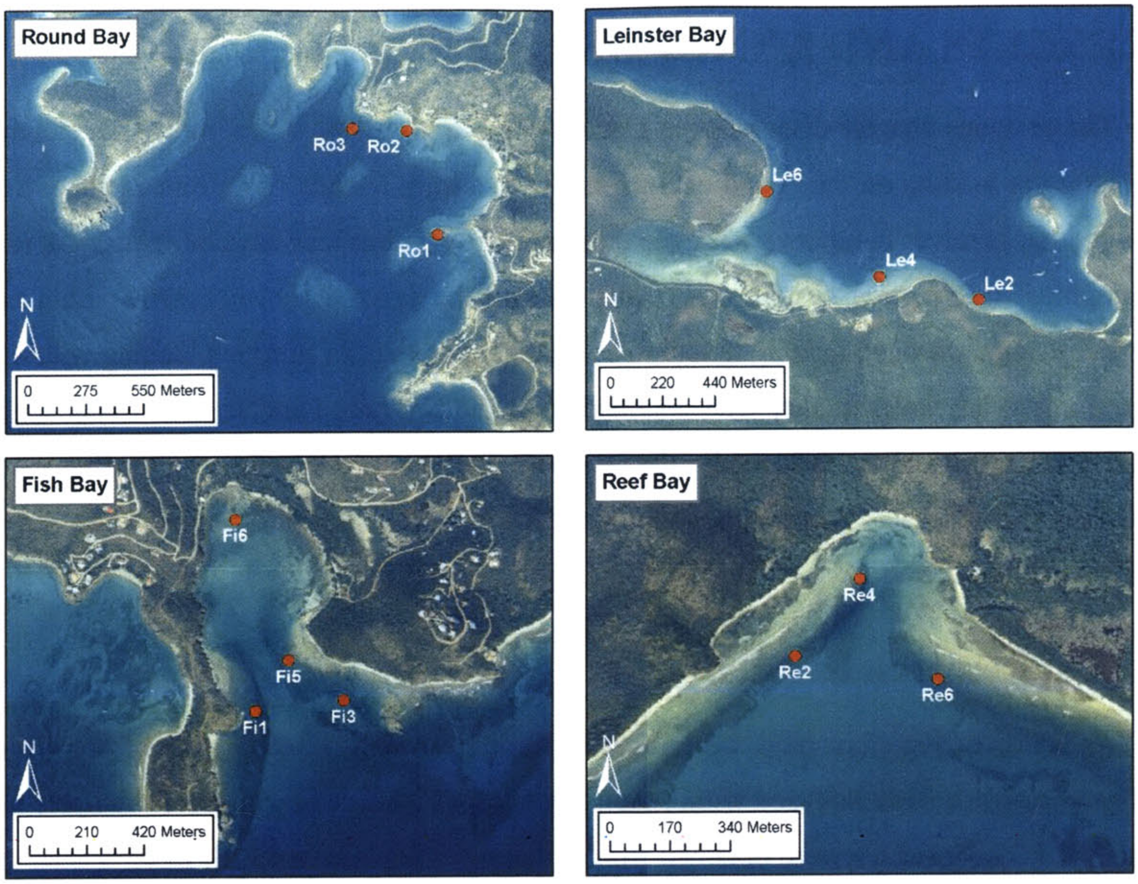

Figure 4.1: Sample site locations for water quality samples

Table 4.1: Average concentrations of nitrate, nitrite, and ammonia within sampled bays

Bay	Classification	Concentration (μM of N)			
		Nitrate	Nitrite	Ammonia	Total
Fish Bay	Developed	1.8	0.0058	BDL	1.8
Leinster Bay	Undeveloped	1.1	0.0063	0.45	1.5
Reef Bay	Undeveloped	1.6	0.0055	BDL	1.6
Round Bay	Developed	1.1	0.0024	0.11	1.2

BDL = below method detection limit

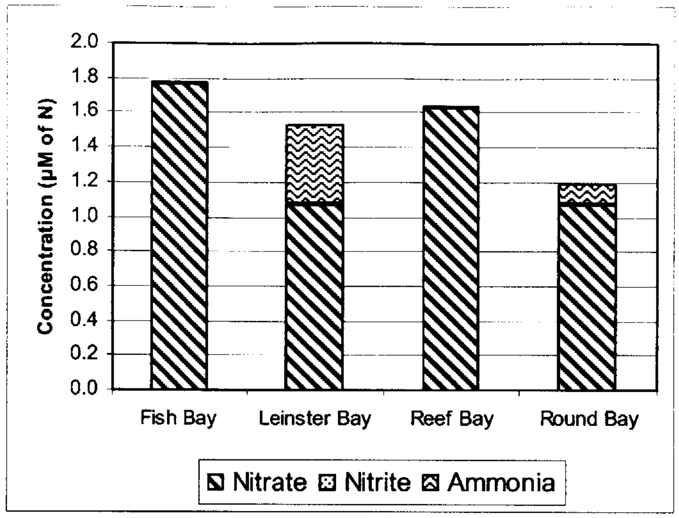

Figure 4.2: Average concentrations of nitrate, nitrite, and ammonia

The data shows that there are differences in nitrogen concentration between the bays but they are not correlated to the development of the watershed. Fish Bay is one of the developed bays and has the highest concentration of nitrogen, but Leinster Bay and Reef Bay, the two undeveloped bays, are both only 0.3 and 0.2 µM less than Fish Bay respectively. Round Bay, the other bay with a developed watershed, has the lowest concentration of nitrogen. Regardless of the precision of the tests, there is no observable correlation between nitrogen concentration and level of development.

The runoff sample had a nitrate concentration of 4.1 µM, a nitrite concentration of 0.036 µM, and an ammonia concentration of 7.8 µM; the runoff has a total nitrogen concentration of 12 µM, which is approximately eight times the nitrogen concentration of the bays. The high presence of ammonia is a possible indicator of septic tank effluent because it is commonly found in high concentrations in wastewater effluent. Although runoff has higher nitrogen concentrations than the bays, it is unlikely that surface runoff contributes greatly to nitrogen loading. Due to climate conditions on the island, storms produce very little runoff, with the exception of large storms such as hurricanes (McCreery, 2007). It would require large storms over the course of many days to produce enough runoff to elevate the concentrations of the bays.

4.2 Geographic Information System Results

Using the program ArcGIS, the physical properties of the bays and watersheds were calculated, as well as the length of roads and number of developments within each watershed. Results are shown in the following sections.

Using the methodology shown in section 3.2, Geographic Information System, the bays and their respective watersheds were delineated. All of the bays on the island are shown in Figure 4.3, while the bay dimensions of the four main study sites is presented in Table 4.2. The bay dimensions for all the bays are presented in Appendix B, Table B.1.

Figure 4.3: Delineation of all the bays around St. John

Table 4.2: Dimensions of the four main study sites

Site	Depth (m)	Surface Area (m^2)	Volume (m^3)
Fish Bay	3.6	4.5×10^5	1.6×10^6
Leinster Bay	5.8	8.5×10^5	5.0×10^6
Reef Bay	5.5	8.6×10^5	4.7×10^6
Round Bay	13.6	1.7×10^6	2.3×10^7

After the dimensions were obtained, the watersheds of each of the bays were delineated, and the number of developments and the lengths of the roads were quantified within each watershed. A map of all the watersheds is shown in Figure 4.4. The number of developments and the lengths of the roads were obtained for each bay, and are shown in Figure 4.5. The surface area of each watershed, the number of developments, and the length of the roads is presented in Table 4.3 for the main study sites and in Appendix B, Table B.2 for all the bays.

Figure 4.4: Watersheds of all bays around St. John

Figure 4.5: Roads and developments on St. John.

Table 4.3: Watershed characteristics of the four main study sites.

Site	Watershed Area (km^2)	Number of Developments	Length of Roads (km)
Fish Bay	6.0	127	16.7
Leinster Bay	2.8	4	2.1
Reef Bay	5.5	14	4.4
Round Bay	1.1	24	4.5

As shown in Figure 4.5, developments are primarily located eastern side (Cruz Bay) and western side (Coral Harbor) of the island. The middle area of the island is the location of the Virgin Islands National Park has very few roads and developments.

4.3 Nitrogen Model Results

As stated earlier, the Nitrogen Loading Model was used to predict the annual nitrogen loading that enters each bay. The results are shown in Table 4.4. The first four bays that were sampled are shown in the first four columns, and the rest of the bays are shown in order of buildings per hectare. The table shows the range of nitrogen loading calculated for each bay as well as the average value. The average values were then divided by the volumes of the bays to obtain the concentration of nitrogen that would result within the bays if there were no other sources and sinks and no tidal flushing. This is to approximate the relative impact of nitrogen loading on the respective bays. Detailed tables of the inputs and outputs to the St. John Nitrogen Loading Model are shown in Appendix D.

A total of 1072 buildings were counted across the island. By multiplying by the average number of people per household of 2.39, there is a total of 2,562 people accounted for in the model (U.S. Census Bureau, 2001). This value is less than the total population of St. John in the year 2000 of 4,149, and visitors are not accounted for: as a result, it is assumed that the model is underestimating the amount of nitrogen loading from wastewater sources.

The average amount of nitrogen loading per bay is 212 kg of N per year, and the average increase of N concentration in the bays without flushing or denitrification is 13.4 μM per year. Assuming an average flushing rate of the bays being one month, the average steady state of the bays is 1.1 μM. Overall, these values are within range of the Gulf of Mexico nitrogen concentrations (National Oceanic and Atmospheric Administration, 2002). The bay with the highest estimated N loading is Coral Harbor (961 kg of N per year), while the bay with the highest annual increase in N is Cruz Bay (130 μM per year). Figure 4.6 shows a map with predicted nitrogen loadings of the watersheds represented in color saturation. It shows that the central portion of the island, which contains the National Park, is predicted to have little nitrogen loading compared to the developed eastern and western portions of the island.

Using the results of the SJNLM, bay characteristics were plotted against average nitrogen loading to determine whether there were any correlations. Figure 4.7 through Figure 4.10 show the number of buildings within each watershed, the area of the watershed, the building density of the watershed, and the percent of the watershed that is impervious versus the total annual nitrogen loading. Linear regression lines were plotted to determine if there was a linear relationship between the results. The graphs suggest that the nitrogen loading has a higher correlation with the number of buildings within the watershed compared than with the other tested watershed characteristics. The model predicts that the number of homes within a watershed has a greater impact on nitrogen loading than the concentration of homes.

The model was also used to calculate and compare nitrogen loading under conditions of no development, current levels of development, and maximum development for each bay. The average results of the three scenarios are shown in Table 4.5. A more detailed table is shown in Appendix D. The results of the scenarios are also plotted in Figure 4.11.

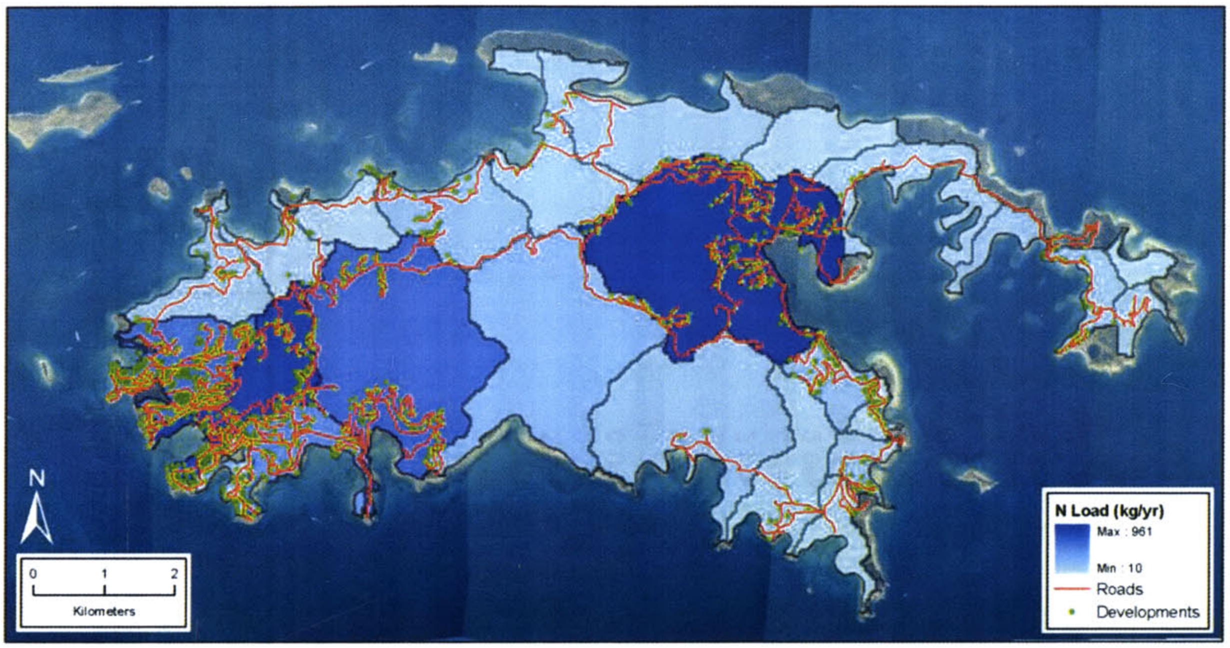

Figure 4.6: SJNLM nitrogen loads of the watersheds on St. John

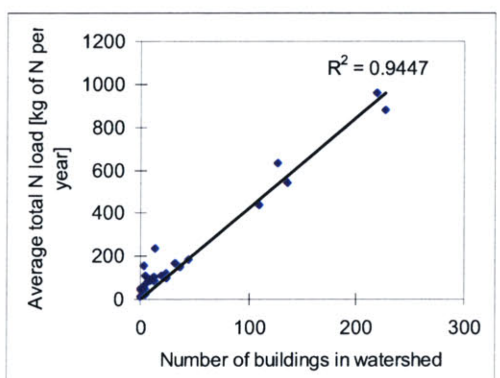

Figure 4.7: Annual nitrogen load vs. number of buildings in watershed

Table 4.4: Results from St. John Nitrogen Loading Model

Bay	No. of buildings	Area of watershed (ha)	Building density (buildings per ha)	% impervious watershed surface area	Total N load delivered to bay (kg of N per year)			Bay Volume (m^3)	Annual increase in nitrogen concentration (µM)
					Minimum	Average	Maximum		
Fish Bay	127	599	0.21	1.0%	501	631	760	1,629,000	22.0
Leinster Bay	4	280	0.01	0.3%	89	110	132	4,966,000	1.3
Reef Bay	14	556	0.03	0.4%	188	237	287	4,741,000	2.8
Round Bay	24	118	0.20	2.0%	112	121	130	23,255,000	0.3
Brown Bay	0	126	0.00	0.0%	34	44	53	466,000	5.3
Caneel Bay	19	131	0.14	2.7%	93	109	125	5,186,000	1.3
Chocolate Hole	45	36	1.25	7.4%	171	184	198	361,000	33.8
Cinnamon Bay	32	182	0.18	1.6%	140	167	194	1,417,000	7.0
Coral Harbor	219	652	0.34	2.7%	794	961	1128	2,569,000	22.1
Cruz Bay	136	172	0.79	9.3%	461	542	624	253,000	129.9
Friis Bay	0	29	0.00	0.0%	8	10	12	293,000	1.9
Great Cruz Bay	227	218	1.04	11.3%	739	877	1014	956,000	55.2
Grootpan Bay	9	171	0.05	0.7%	72	89	105	2,554,000	2.0
Haulover Bay	4	28	0.14	2.8%	19	22	26	281,000	4.8
Hawksnest Bay	14	90	0.16	2.0%	71	80	89	898,000	5.6
Hurricane Hole	5	155	0.03	0.8%	59	71	82	20,716,000	0.2
John's Folly Bay	24	52	0.46	2.9%	89	99	109	522,000	12.1
Johnson Bay	37	77	0.48	3.4%	134	151	167	771,000	12.4
Lameshur Bay	3	420	0.01	0.2%	126	156	187	6,219,000	1.4
Maho Bay	12	187	0.06	0.8%	85	104	123	6,628,000	0.9
Newfound Bay	0	31	0.00	0.0%	8	11	13	311,000	1.9
Privateer Bay	1	40	0.02	1.3%	14	17	21	402,000	2.4
Redezvous Bay	109	118	0.93	5.9%	379	436	492	8,698,000	3.1
Salt Pond Bay	2	72	0.03	3.3%	26	33	40	724,000	2.5
Trunk Bay	5	88	0.06	0.8%	38	47	55	875,000	3.1

Table 4.5: SJNLM results for undeveloped, current, and maximum development scenarios

Bay	Current development	Undeveloped		Maximum development	
	Total N load delivered to bay (kg of N per year)	Total N load delivered to bay (kg of N per year)	% decrease of N from current development	Total N load delivered to bay (kg of N per year)	% increase in N from current development
Fish Bay	631	207	67%	2729	330%
Leinster Bay	110	97	12%	1389	1160%
Reef Bay	237	192	19%	2547	970%
Round Bay	121	41	66%	589	390%
Brown Bay	44	44	0%	620	1320%
Caneel Bay	109	45	58%	650	500%
Chocolate Hole	184	12	93%	184	0%
Cinnamon Bay	167	63	62%	878	430%
Coral Harbor	961	225	77%	3066	220%
Cruz Bay	542	59	89%	823	50%
Friis Bay	10	10	0%	143	1320%
Great Cruz Bay	877	75	91%	1034	20%
Grootpan Bay	89	59	33%	826	830%
Haulover Bay	22	10	56%	140	530%
Hawksnest Bay	80	31	61%	463	480%
Hurricane Hole	71	54	24%	772	990%
John's Folly Bay	99	18	82%	263	170%
Johnson Bay	151	27	82%	385	160%
Lameshur Bay	156	145	7%	2023	1190%
Maho Bay	104	65	38%	900	770%
Newfound Bay	11	11	0%	155	1340%
Privateer Bay	17	14	19%	199	1050%
Redezvous Bay	436	41	91%	558	30%
Salt Pond Bay	33	25	23%	358	1000%
Trunk Bay	47	38	35%	426	810%

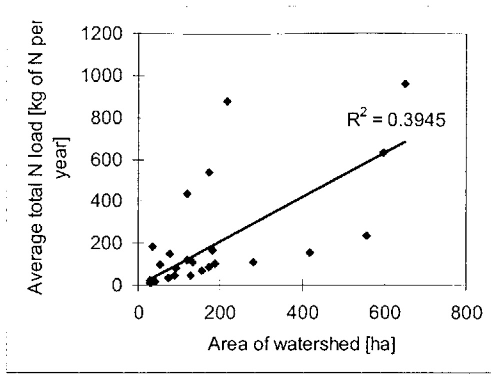

Figure 4.8: Annual nitrogen load vs. area of watershed

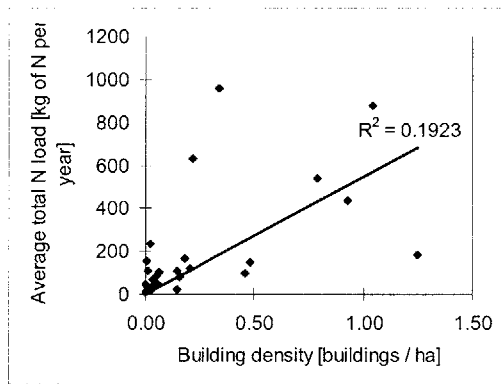

Figure 4.9: Annual nitrogen load vs. building density

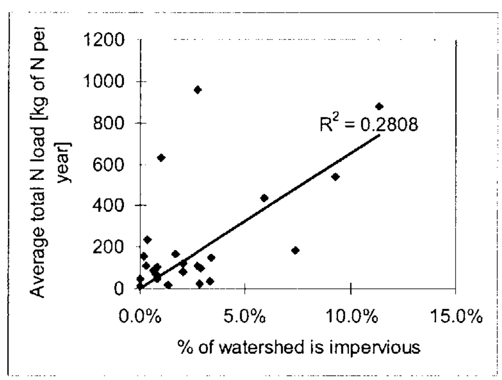

Figure 4.10: Annual nitrogen load vs. percent of watershed as an impervious surface

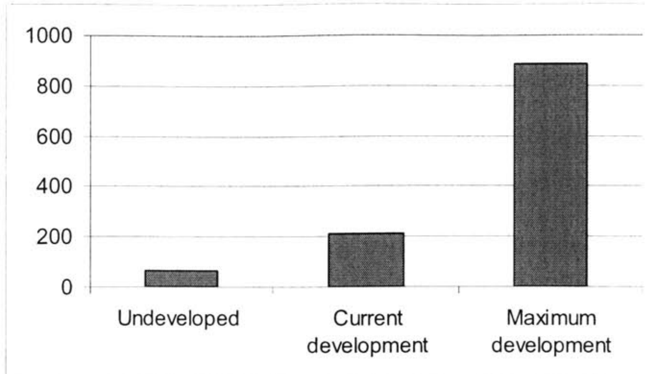

Figure 4.11: SJNLM average results for undeveloped, current, and maximum development scenarios

On average, bays under undeveloped conditions had 48% less nitrogen loading than under current conditions, while bays under maximum development conditions increased nitrogen loading by 640% or over six times the current conditions. The number of buildings under maximum development conditions is 5770, over five times more buildings than the current number of buildings on St. John. The population of the island would, likewise, increase by five-fold. These results show the impact that could occur if development on the island was not restricted by the Virgin Islands National Park. The results also show that, on average, the current development has doubled the nitrogen loading compared to the island without development. Although substantial, the current level of development is much less than under maximum conditions.

4.4 National Park Service Water Quality Data Analysis

The historical water-quality data from the bays was used to evaluate the correlation between nitrogen concentrations within the bays and development. The National Park Service (NPS) recorded concentrations of nitrate (NO_3^-), nitrite (NO_2^-) and ammonia (NH_3). The sum of nitrate and nitrite concentrations was also recorded due to the limited amount of nitrite. For this thesis, the nitrate and nitrite concentrations are combined while ammonia concentrations are independent.

The watersheds of the bays were classified by the NPS into undeveloped, partially developed, and developed watersheds. For days where multiple samples were taken on the same day, all the values were averaged together to provide a single representative concentration for use in the correlative study. Representative concentrations for the bays were graphed using Microsoft Excel. A linear regression of concentration versus time was computed for the sum of nitrate and nitrite concentrations and for ammonia concentrations. The historical data for Fish Bay, Leinster Bay, and Reef Bay is shown in Figure 4.12, Figure 4.13, and Figure 4.14 respectively (Round Bay had no water quality data). Figure 4.15 shows the sum of nitrate and nitrite concentrations for the three bays superimposed on each other. A summary of the NPS water quality data is shown in Table 4.6. Graphs of the historical nitrogen data are shown in Appendix E. Figure 4.16 shows the average concentrations and slopes of the linear regressions for combined nitrate and nitrite as well as ammonia. The values are arranged according to the degree of watershed development.

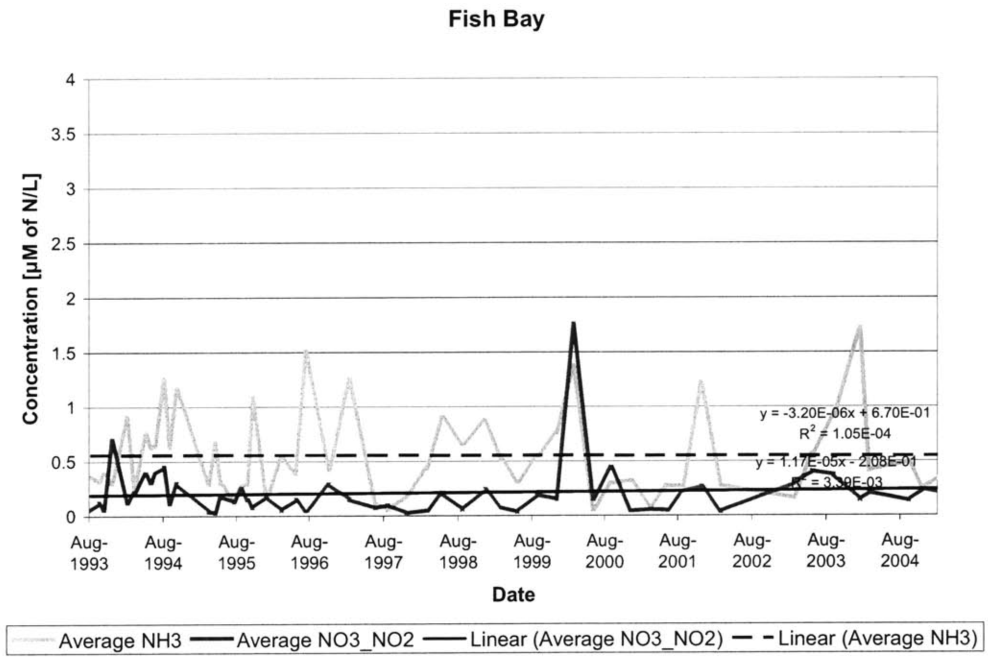

Figure 4.12: Fish Bay National Park Service water quality data

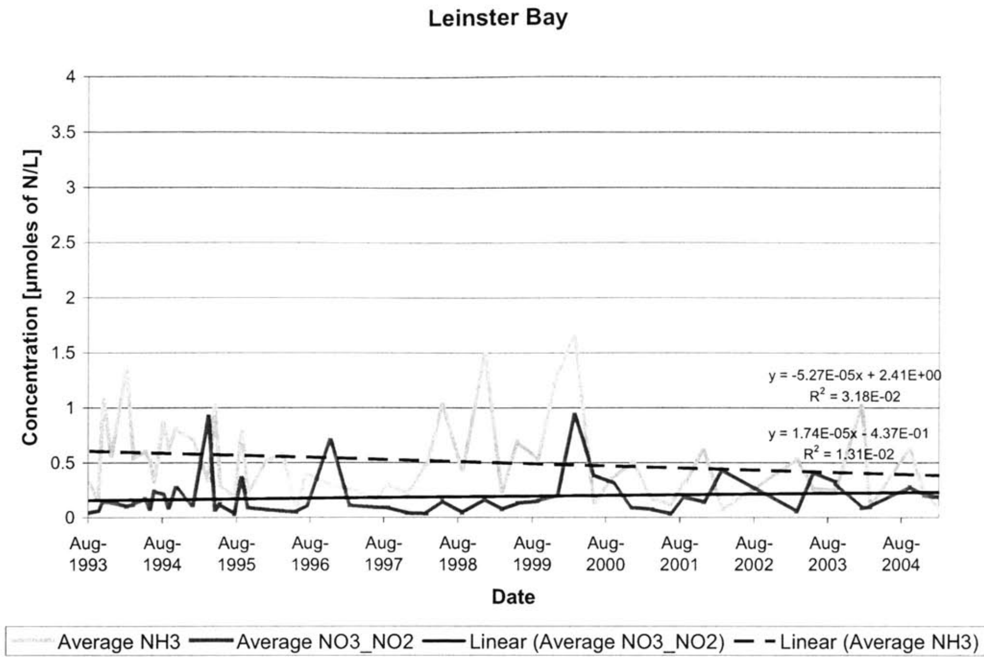

Figure 4.13: Leinster Bay National Park Service water quality data

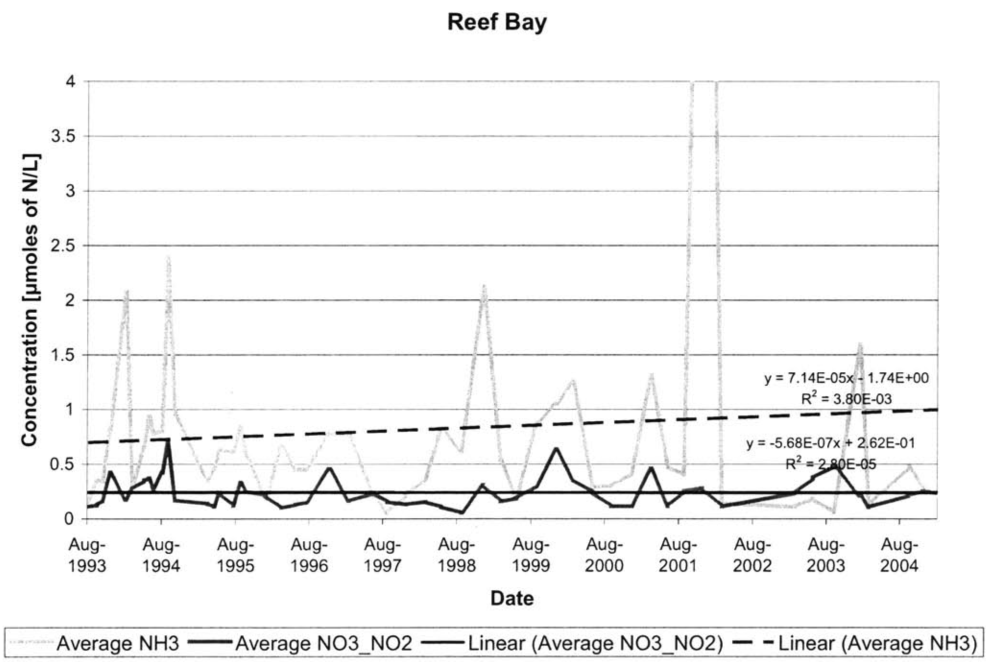

Figure 4.14: Reef Bay National Park Service water quality data

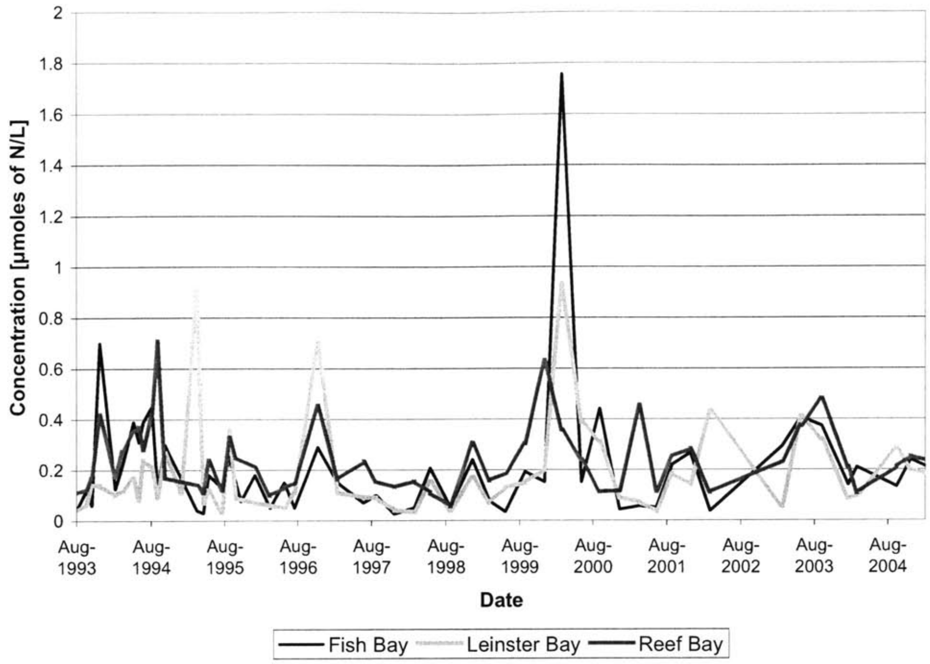

Figure 4.15: Fish Bay, Leinster Bay, and Reef Bay nitrate and nitrite National Park Service water quality data

Inspection of the nitrogen data shows that ammonia concentrations are regularly higher than combined nitrate and nitrite concentrations. This result is different for our own field tests, which showed nitrate values being larger than ammonia.

Table 4.6 shows that the NO_3^- and NO_2^- concentrations are only slightly higher for developed watersheds than undeveloped watersheds, while the difference in NH_3 concentrations between the two classifications is greater. NO_3^- and NO_2^- have increased slightly as the years progressed, but the average rate of increase has been low and generally uniform throughout all the tested sites. NH_3 concentrations have shown a decrease within the past ten years, but the rate of decline does not vary consistently between the different classes of watersheds. The highest concentrations are found on developed watersheds, but the ranges of values are very similar to the undeveloped watersheds. Overall, the data shows that there are no substantial differences in nitrogen concentrations between undeveloped, partially developed, and developed watersheds.

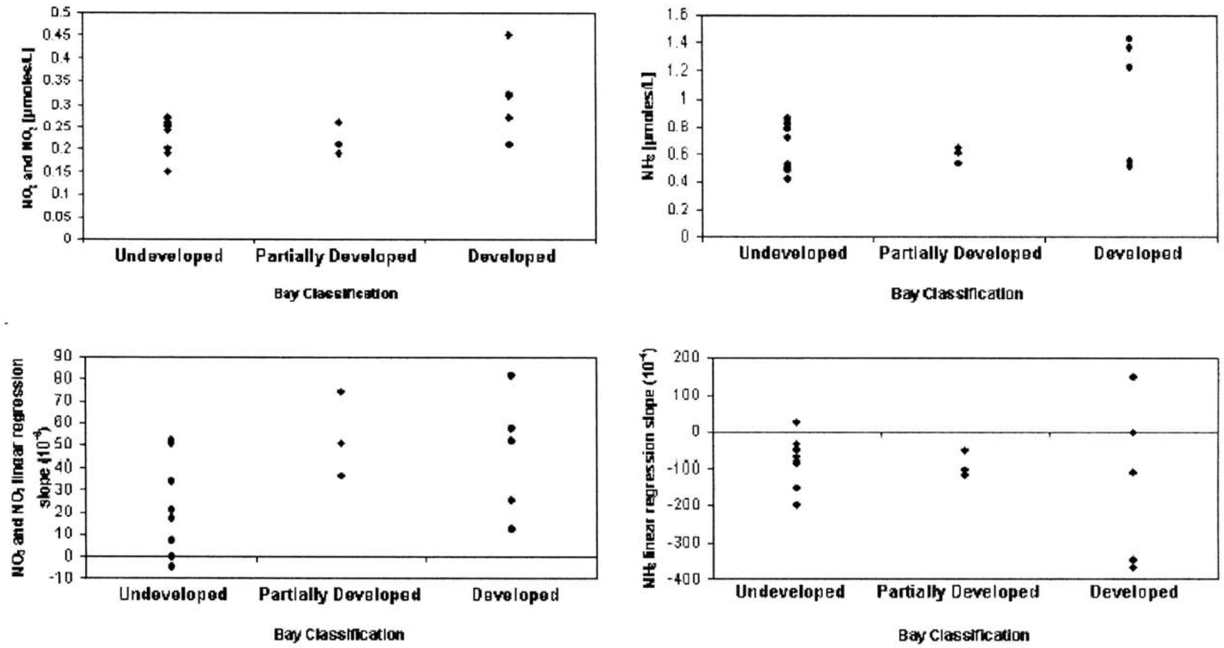

Figure 4.15: Combined NO_3^- and NO_2^- and NH_3 average concentrations and time rate of change in concentration (linear regression slopes), organized by watershed classification

Table 4.6: Summary of National Park Service N concentrations for undeveloped, partially developed, and developed watersheds

Watershed classification	Number of bays	Average NO_3 and NO_2 [□moles/L]	Average NH_3 [□moles/L]	NO_3 and NO_2 linear regression slope (10^{-8})	NH_3 linear regression slope (10^{-8})
Undeveloped	8	0.23	0.64	22	-79
Partially developed	3	0.22	0.60	54	-92
Developed	5	0.29	1.02	46	-137

Some of the graphs of nitrogen concentrations show peaks in nitrate and ammonia that are correlated to one another. Usually, ammonia peaks before nitrate or nitrite but occasionally, the two peaks coincide. Most of the peaks are up to three months apart, but some coincide on the same sampling day. As previously mentioned in Section 3.4, it is possible that runoff from storms is carrying high concentrations of nitrogen that are causing peaks in nitrogen loading. Figure 4.17 shows nitrogen concentrations in Trunk Bay superimposed on daily rainfall data from the watershed, and Figure 4.18 shows the concentrations of nitrogen plotted against the total rainfall over the seven days prior to the day of sampling. The analysis assumes that within seven days, all the runoff from a major storm would reach the estuary.

Figure 4.18 shows that nitrogen concentrations are scattered and there is no correlation between the total rainfall over seven days prior to the date of sampling and nitrogen concentrations. Therefore, the majority of nitrogen entering the bays appears to be either from groundwater discharges or from water exchange with the ocean.

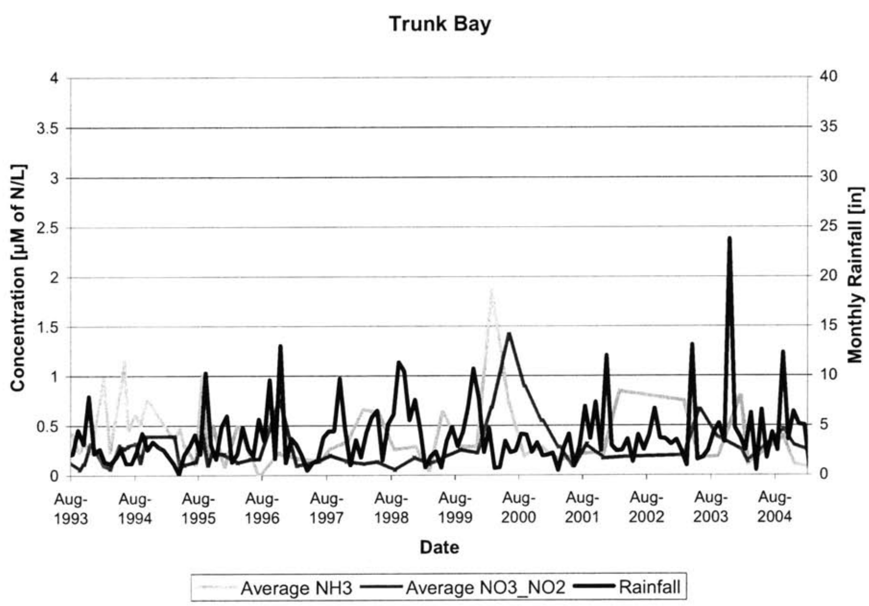

Figure 4.17: Trunk Bay National Park Service historical ammonia concentrations, nitrate and nitrite concentrations, and rainfall

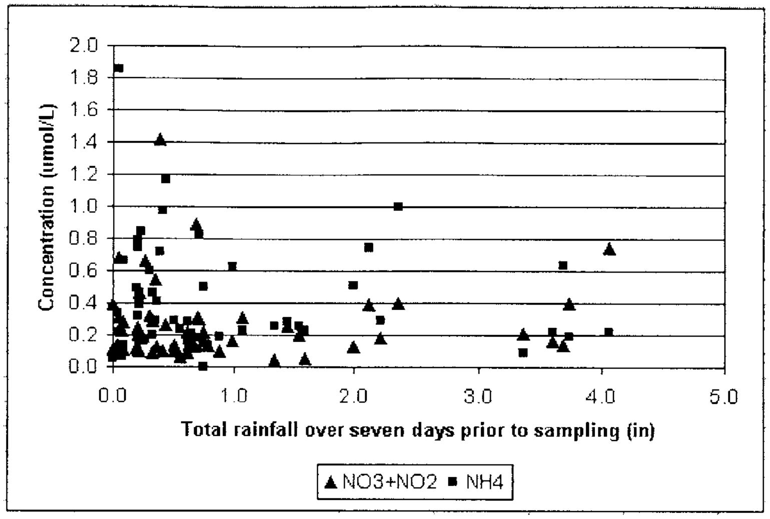

Figure 4.18: Concentration of nitrate, nitrite and ammonia vs. total rainfall over seven days prior to sampling

While the SJNLM shows that development on the island does significantly increase nitrogen loading, the results from the field sampling and the NPS water quality data does not support this conclusion. The following chapter will discuss the conclusions of the thesis and recommendations for future work.

5 CONCLUSIONS AND RECOMMENDATIONS

This study of the bays of St. John, U.S. Virgin Islands, used results obtained from water quality samples, a nitrogen loading model (Saint John Nitrogen Loading Model), and historical water quality data from the National Park Service to determine if there is a correlation between the development of a watershed and the amount of nitrogen loading. The following sections discuss the conclusions of the analysis and possible recommendations.

5.1 Conclusions

The Saint John Nitrogen Loading Model (SJNLM) predicts that the current nitrogen loading into the bays is approximately twice the amount of nitrogen loading if the island was undeveloped, but both values are small relative to the volume of the bays. While the field data is inconclusive, the National Park Service water quality data show little correlation between nitrogen concentrations within the bays and the level of development. The sum of nitrate and nitrite concentrations within the bays has been increasing slightly, but there is no observable relationship between the rate of increase and whether the bay is developed or not. Overall, there is little evidence that the level of development within the watersheds is causing excessive nitrogen loading to the bays, and is therefore unlikely that the increased nitrogen loading from developments is having an adverse impact on the coral reefs.

One possible reason for the lack of impact by developments is that terrestrial nitrogen sources are not the major contributor of nitrogen into the bays. According to work done by another member of the project team, the amount of nitrogen loading is approximately two orders of magnitude less than the biological fluxes within the bays (Walker, 2007). This means that terrestrial nitrogen provides only a small contribution to the total nitrogen within the bays. The biological processes within the bays can overshadow the impact of nitrogen from terrestrial sources.

Clearly, the presence of the National Park also prevents nitrogen from becoming a serious threat to the bays. The park prevents development from occurring on the majority of the island, but without the park nitrogen loading could increase considerably. This scenario is supported by the SJNLM which predicts that nitrogen concentrations would increase by more than six times the current conditions if the entire island had the same level of development as the most developed part of St. John. This shows that maintaining the current level of development is important to ensure the protection of the coral reefs.

5.2 Recommendations

While the SJNLM predicts limited nitrogen loading for St. John, other islands within the Caribbean can have excessive nitrogen loading from developments; this model can be applied to other islands to address this issue. Many of the parameters used in the SJNLM were assigned values from studies conducted on Puerto Rico. To improve the accuracy of the model, sampling of nitrogen concentrations throughout the island to be modeled should be conducted. Groundwater sampling would help ascertain the amount of nitrogen being transported through the groundwater into the bays, while nitrogen concentrations within the soil would be used to obtain vegetation fluxes and vadose zone denitrification on the island. Also, water samples of septic tank effluent would improve the accuracy of nitrogen loading estimates from anthropogenic sources.

It is most likely that the degradation of the coral reefs is the result of other human-caused factors such as sediment loading or rising sea temperatures (McCreery, 2007). Physical trauma to the reefs from boats or divers has also been shown to cause significant, long-term damage to the reefs. Therefore, other studies on St. John should focus on those dangers instead of nitrogen loading from terrestrial sources.

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7 APPENDICIES

A. Calibration Curves for Hach DR/2010 Spectrophotometer

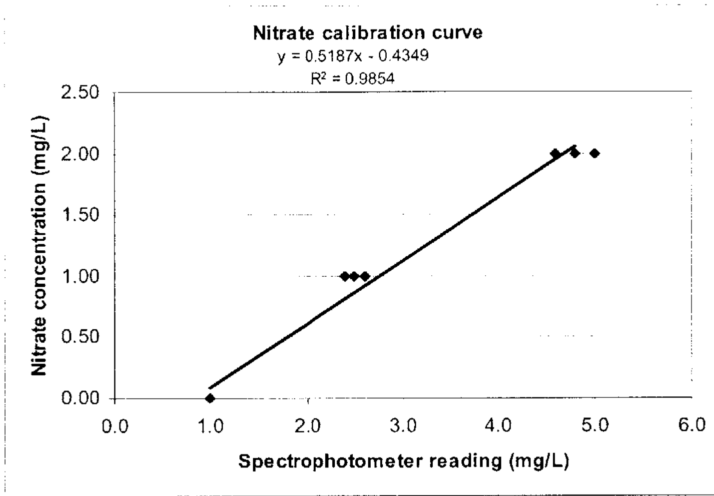

Figure A.1: Nitrate calibration curve

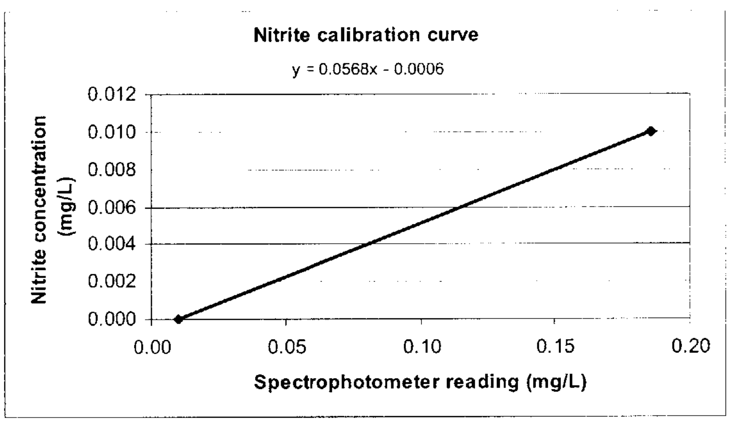

Figure A.2: Nitrite calibration curve

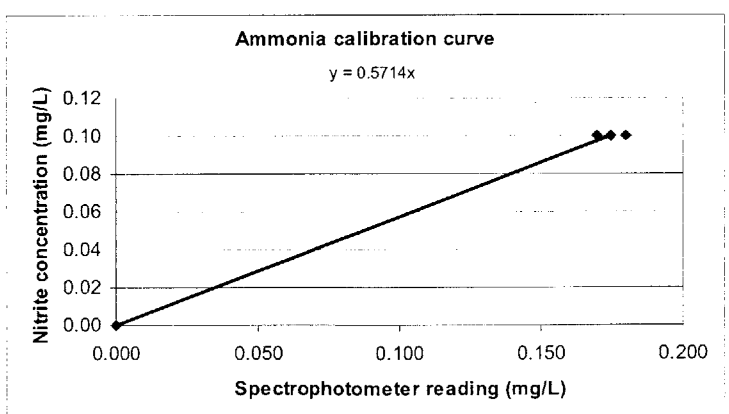

Figure A.3: Ammonia calibration curve

B. GIS Figures and Tables

Figure B.1: Aerial photo of St. John.

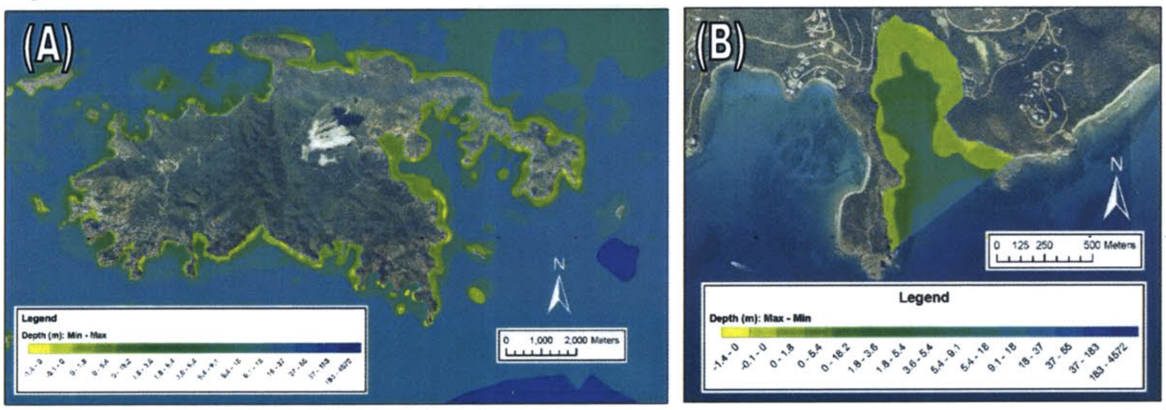

Figure B.2: Bathymetric chart of water depths (A) around St. John and (B) in Fish Bay (values are relative to MLLW).

Figure B.3: Digital elevation model of St. John.

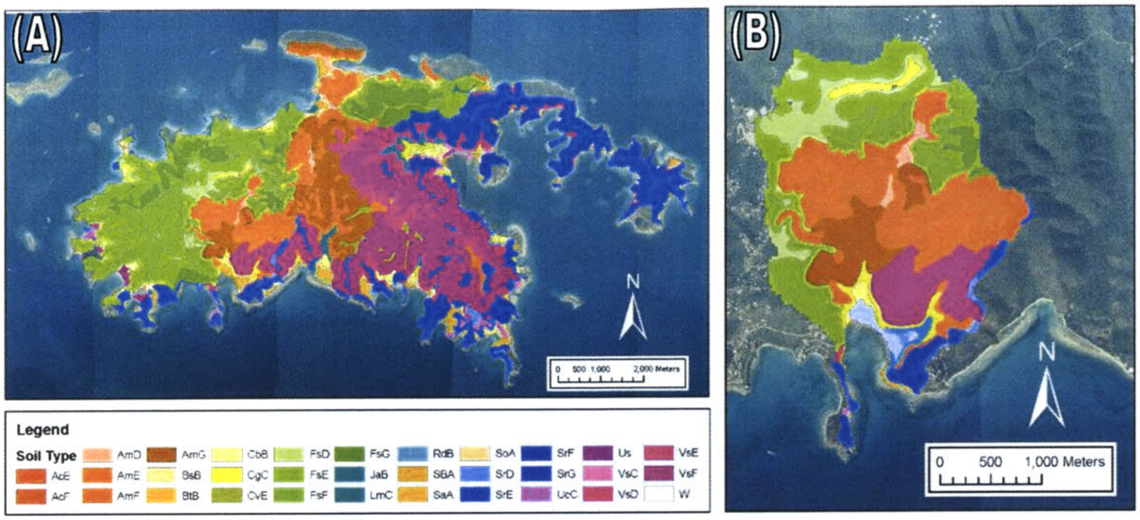

Figure B.4: Soil types (A) on St. John and (B) in the Fish Bay watershed only.
See (Natural Resources Conservation Service, 2006) for more information about the soil types.

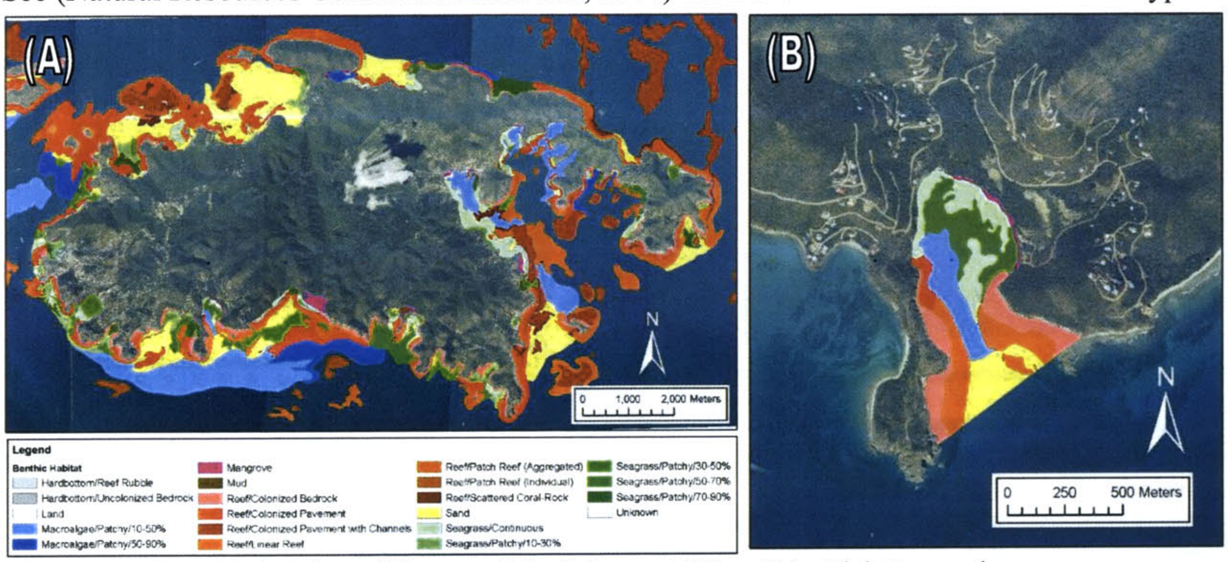

Figure B.5: Benthic habitats (A) around St. John and (B) within Fish Bay only.

Table B.1: Dimensions of all the bays on St. John

Site	Average Depth (m)	Surface Area (m^2)	Volume (m^3)
Brown Bay	3.4	1.4E+05	4.7E+05
Caneel Bay	8.4	6.2E+05	5.2E+06
Chocolate Hole	4.4	1.6E+05	7.0E+05
Cinnamon Bay	4.6	3.1E+05	1.4E+06
Coral Harbor	3.7	6.9E+05	2.6E+06
Cruz Bay	1.9	1.4E+05	2.5E+05
Drunk Bay	3.8	1.8E+05	6.8E+05
East End Bay	2.2	6.6E+04	1.4E+05
Fish Bay	3.6	4.5E+05	1.6E+06
Friis Bay	2.7	6.1E+04	1.7E+05
Great Cruz Bay	3.4	2.8E+05	9.6E+05
Grootpan/Kiddel Bay	10.8	2.4E+05	2.6E+06
Haulover Bay	4.0	1.7E+05	6.7E+05
Hawksnest Bay	8.0	5.1E+05	4.1E+06
Hurricane Hole	11.4	1.8E+06	2.1E+07
Johns Folly Bay	2.9	2.0E+05	5.7E+05
Johnson Bay	2.7	1.1E+05	3.1E+05
Lameshur Bay	6.5	9.6E+05	6.2E+06
Leinster Bay	5.8	8.5E+05	5.0E+06
Maho/Francis Bay	8.2	8.1E+05	6.6E+06
Mennebeck Bay	4.8	1.5E+05	7.0E+05
Newfound Bay	2.5	1.3E+05	3.1E+05
Privateer Bay	5.4	2.3E+05	1.2E+06
Reef Bay	5.5	8.6E+05	4.7E+06
Rendezvous Bay	8.4	1.0E+06	8.7E+06
Round Bay	13.6	1.7E+06	2.3E+07
Salt Pond Bay	10.7	4.1E+05	4.3E+06
Trunk Bay	4.1	1.8E+05	7.4E+05
Turner Bay	2.8	5.7E+04	1.6E+05

Table B.2: Watershed characteristics for all bays.

Site	Watershed Area (km^2)	Number of Developments	Length of Roads (km)
Brown Bay	1.26	0	0.0
Caneel Bay	1.31	19	4.4
Chocolate Hole	0.36	45	3.2
Cinnamon Bay	1.82	32	5.2
Coral Harbor	6.52	219	30.4
Cruz Bay	1.72	136	7.6
Fish Bay	5.99	127	16.7
Friis Bay	0.29	0	0.0
Great Cruz Bay	2.18	227	16.8
Grootpan/Kiddel Bay	1.71	9	2.3
Haulover Bay	0.28	4	2.1
Hawksnest Bay	0.90	14	3.7
Hurricane Hole	1.55	5	2.8
John's Folly Bay	0.52	24	2.1
Johnson Bay	0.77	37	4.1
Lameshur Bay	4.20	3	2.2
Leinster Bay	2.80	4	2.1
Maho Bay	1.87	12	3.0
Newfound Bay	0.31	0	0.0
Privateer Bay	0.40	1	1.6
Rendezvous Bay	1.18	109	9.6
Reef Bay	5.56	14	4.4
Round Bay	1.18	24	4.5
Salt Pond Bay	0.72	2	2.3
Trunk Bay	0.88	5	1.5

C. Results of Nitrogen Sampling from Bays

Table C.1: Nitrogen samples site locations and date of sampling and testing

Date		Site	Sample	Latitude				Longitude			
Sample obtained	Sample tested			Direction	Degrees	Minutes	Seconds	Direction	Degrees	Minutes	Seconds
1/19	1/20	Round Bay	1	N	18	20	19.7	W	64	40	36.2
1/19	1/20	Round Bay	2	N	18	20	35.5	W	64	40	40.9
1/19	1/21	Runoff	-								
1/22	1/22	Leinster Bay	2	N	18	21	49.2	W	64	43	31.3
1/22	1/22	Leinster Bay	4	N	18	21	52.4	W	64	43	44.7
1/22	1/22	Leinster Bay	6	N	18	22	3.9	W	64	44	0.02
1/23	1/23	Fish Bay	1	N	18	No GPS	No GPS	W	64	No GPS	No GPS
1/23	1/23	Fish Bay	3	N	18	" "	" "	W	64	" "	" "
1/23	1/23	Fish Bay	5	N	18	" "	" "	W	64	" "	" "
1/23	1/23	Fish Bay	6	N	18	" "	" "	W	64	" "	" "
1/24	1/24	Reef Bay	2	N	18	19	15.2	W	64	44	59.1
1/24	1/24	Reef Bay	4	N	18	19	22.2	W	64	44	53.2
1/24	1/24	Reef Bay	6	N	18	19	13.1	W	64	44	46.1
1/26	1/26	Round Bay	1	N	18	20	35.8	W	64	40	49.3

Table C.2: Nitrogen sample concentrations

Site	Sample	Nitrate (mg/L)			Nitrite (mg/L)			Ammonia (mg/L)			Total N
		Display	Actual	□ M of N	Display	Actual	□ M of N	Display	Actual	□ M of N	□ M of N
Round Bay	1	1.2	0.19	3.0	0.014	0.000195	0.0042	-0.02	-0.011	-0.67	3.0
Round Bay	2	1.0	0.08	1.4	0.013	0.000138	0.0030	0.02	0.011	0.67	2.0
Runoff	-	0.4	0.26	4.1	0.012	0.001672	0.0363	0.07	0.133	7.84	12.0
Leinster Bay	2	1.3	0.24	3.9	0.016	0.000309	0.0067	0.09	0.051	3.03	6.9
Leinster Bay	4	0.9	0.03	0.5	0.016	0.000309	0.0067	0.00	0.000	0.00	0.5
Leinster Bay	6	0.7	-0.07	-1.2	0.015	0.000252	0.0055	-0.05	-0.029	-1.68	-1.2
Fish Bay	1	0.9	0.03	0.5	0.018	0.000422	0.0092	-0.02	-0.011	-0.67	0.5
Fish Bay	3	0.9	0.03	0.5	0.015	0.000252	0.0055	-0.01	-0.006	-0.34	0.5
Fish Bay	5	1.2	0.19	3.0	0.013	0.000138	0.0030	-0.01	-0.006	-0.34	3.0
Fish Bay	6	1.2	0.19	3.0	0.015	0.000252	0.0055	-0.02	-0.011	-0.67	3.0
Reef Bay	2	1.2	0.19	3.0	0.015	0.000252	0.0055	-0.01	-0.006	-0.34	3.0
Reef Bay	4	0.9	0.03	0.5	0.015	0.000252	0.0055	-0.03	-0.017	-1.01	0.5
Reef Bay	6	1.0	0.08	1.4	0.015	0.000252	0.0055	0.00	0.000	0.00	1.4
Round Bay	1	0.7	-0.07	-1.2	0.010	0.000000	0.0000	0.01	0.006	0.34	-0.8

Table C.3: Nitrogen sample comments

Site	Sample	Comments
Round Bay	1	
Round Bay	2	
Runoff	-	Diluted 3/10. Turbid.
Leinster Bay	2	First ammonia test 0.13 mg/L. Second ammonia test 0.05 mg/L
Leinster Bay	4	
Leinster Bay	6	
Fish Bay	1	
Fish Bay	3	
Fish Bay	5	
Fish Bay	6	
Reef Bay	2	Ammonia tested with distilled water -0.09 mg/L
Reef Bay	4	
Reef Bay	6	
Round Bay	1	

D. St. John Nitrogen Loading Model Tables and Graphs

Table D.1: St. John census data of households with septic tanks and average household size
Source: U.S. Census Bureau, 2002

County	Total Houses	Public	Septic tank or cesspool	Other	% Septic or other	Average household size
Central	431	78	318	35	82.90%	2.27
Coral	383	23	306	54	93.99%	2.13
Cruz	1529	265	1197	67	82.67%	2.51
East	47	5	34	8	89.36%	1.9

Table D.2: St. John Nitrogen Loading Model watershed inputs

Bay	No. of buildings	Watershed area (ha)	Impervious surfaces (ha)	Buildings within 200 m from shore	% of watershed containing roads	% of buildings within Central county	% of buildings within Coral Bay county	% of buildings within Cruz Bay county	% of buildings within East End county	% of houses with septic systems or other	Average number of people per household
Reef Bay	14	556	0.0	1	0.28%	50%	50%	0%	0%	88%	2.20
Fish Bay	127	599	0.0	5	0.94%	10%	0%	90%	0%	83%	2.49
Round Bay	24	118	0.0	24	1.34%	0%	0%	0%	100%	89%	1.90
Leinster Bay	4	280	0.0	2	0.25%	100%	0%	0%	0%	82%	2.27
Coral Harbor	219	652	0.0	45	1.56%	10%	90%	0%	0%	93%	2.14
Lameshur Bay	3	420	0.0	3	0.16%	100%	0%	0%	0%	82%	2.27
Great Cruz Bay	227	218	10.9	57	2.82%	0%	0%	100%	0%	83%	2.51
Maho/ Bay	12	187	0.0	4	0.58%	100%	0%	0%	0%	82%	2.27
Cinnamon Bay	32	182	0.0	11	1.05%	100%	0%	0%	0%	82%	2.27
Cruz Bay	136	172	8.6	39	1.61%	0%	0%	100%	0%	83%	2.51
Grootpan Bay	9	171	0.0	3	0.48%	100%	0%	0%	0%	82%	2.27
Hurricane Hole	5	155	0.0	5	0.65%	0%	0%	0%	100%	89%	1.90
Caneel Bay	19	131	1.3	9	1.20%	100%	0%	0%	0%	82%	2.27
Brown Bay	0	126	0.0	0	0.00%	0%	0%	0%	0%	0%	0.00
Redezvous Bay	109	115	0.0	42	2.81%	0%	0%	100%	0%	83%	2.51
Hawksnest Bay	14	90	0.0	10	1.49%	100%	0%	0%	0%	82%	2.27
Trunk Bay	5	88	0.0	2	0.63%	100%	0%	0%	0%	82%	2.27
Johnson Bay	37	77	0.0	20	1.79%	100%	0%	0%	0%	82%	2.27
Salt Pond Bay	2	72	0.0	2	0.98%	100%	0%	0%	0%	82%	2.27
Johns Folly Bay	24	52	0.0	14	1.32%	100%	0%	0%	0%	82%	2.27
Privateer Bay	1	40	0.0	0	1.21%	100%	0%	0%	0%	82%	2.27
Chocolate Hole	45	36	0.0	30	3.20%	0%	0%	100%	0%	83%	2.51
Newfound Bay	0	31	0.0	0	0.00%	0%	0%	0%	0%	0%	0.00
Friis Bay	0	29	0.0	0	0.00%	0%	0%	0%	0%	0%	0.00
Haulover Bay	4	28	0.0	2	2.31%	0%	0%	0%	100%	89%	1.90

Table D.3: Saint John Nitrogen Loading Model current conditions results summary

Bay	No. of buildings	Area of watershed (ha)	Length of roads (km)	Building density (buildings per ha)	% impervious watershed surface area	Minimum total N load delivered to bay (kg of N per year)	Maximum total N load delivered to bay (kg of N per year)	Average total N load delivered to bay (kg of N per year)	% N loading from atmospheric deposition	% N loading from developments	Bay Volume (m3)	Annual increase in nitrogen concentration (µmoles/L)
Brown Bay	0	126	0.0	0.00	0.0%	34	53	44	100%	0%	4.66E+05	5.3
Caneel Bay	19	131	4.4	0.14	2.7%	93	125	109	40%	60%	5.19E+06	1.3
Chocolate Hole	45	36	3.2	1.25	7.4%	171	198	184	6%	94%	3.61E+05	33.8
Cinnamon Bay	32	182	5.2	0.18	1.6%	140	194	167	36%	64%	1.42E+06	7.0
Coral Harbor	219	652	30.4	0.34	2.7%	794	1128	961	77%	23%	2.57E+06	22.1
Cruz Bay	136	172	7.6	0.79	9.3%	461	624	542	89%	11%	2.53E+05	129.9
Fish Bay	127	599	16.7	0.21	1.0%	501	760	631	67%	33%	1.63E+06	22.0
Friis Bay	0	29	0.0	0.00	0.0%	8	12	10	0%	100%	2.93E+05	1.9
Great Cruz Bay	227	218	16.8	1.04	11.3%	739	1014	877	91%	9%	9.56E+05	55.2
Grootpan Bay	9	171	2.3	0.05	0.7%	72	105	89	35%	65%	2.55E+06	2.0
Haulover Bay	4	28	2.1	0.14	2.8%	19	26	22	58%	42%	2.81E+05	4.8
Hawksnest Bay	14	90	3.7	0.16	2.0%	71	89	80	64%	36%	8.98E+05	5.6
Hurricane Hole	5	155	2.8	0.03	0.8%	59	82	71	28%	72%	2.07E+07	0.2
John's Folly Bay	24	52	2.1	0.46	2.9%	89	109	99	83%	17%	5.22E+05	12.1
Johnson Bay	37	77	4.1	0.48	3.4%	134	167	151	84%	16%	7.71E+05	12.4
Lameshur Bay	3	420	2.2	0.01	0.2%	126	187	156	9%	91%	6.22E+06	1.4
Leinster Bay	4	280	2.1	0.01	0.3%	89	132	110	13%	87%	4.97E+06	1.3
Maho Bay	12	187	3.0	0.06	0.8%	85	123	104	39%	61%	6.63E+06	0.9
Newfound Bay	0	31	0.0	0.00	0.0%	8	13	11	0%	100%	3.11E+05	1.9
Privateer Bay	1	40	1.6	0.02	1.3%	14	21	17	17%	83%	4.02E+05	2.4
Redezvous Bay	109	118	9.6	0.93	5.9%	379	492	436	91%	9%	8.70E+06	3.1
Reef Bay	14	556	4.4	0.03	0.4%	188	287	237	19%	81%	4.74E+06	2.8
Round Bay	24	118	4.5	0.20	2.0%	112	130	121	70%	30%	2.33E+07	0.3
Salt Pond Bay	2	72	2.3	0.03	3.3%	26	40	33	18%	82%	7.24E+05	2.5
Trunk Bay	5	88	1.5	0.06	0.8%	38	55	47	37%	63%	8.75E+05	3.1

Table D.4: St. John Nitrogen Loading Model undeveloped conditions results summary

Bay	Area of watershed (ha)	Total N load delivered to bay (kg of N per year)	Maximum total N load delivered to bay (kg of N per year)	Average total N load delivered to bay (kg of N per year)	% decrease of N from current conditions	Bay Volume (m3)	Annual increase in nitrogen concentration (µmoles/L)
Brown Bay	126	34	53	44	0%	4.66E+05	5.3
Caneel Bay	131	36	55	45	58%	5.19E+06	0.5
Chocolate Hole	36	10	15	12	93%	3.61E+05	1.9
Cinnamon Bay	182	50	76	63	62%	1.42E+06	2.5
Coral Harbor	652	177	273	225	77%	2.57E+06	4.9
Cruz Bay	172	47	72	59	89%	2.53E+05	13.2
Fish Bay	599	163	251	207	67%	1.63E+06	7.2
Friis Bay	29	8	12	10	0%	2.93E+05	1.9
Great Cruz Bay	218	59	91	75	91%	9.56E+05	4.4
Grootpan Bay	171	47	72	59	33%	2.55E+06	1.3
Haulover Bay	28	8	12	10	56%	2.81E+05	1.9
Hawksnest Bay	90	24	38	31	61%	8.98E+05	1.9
Hurricane Hole	155	42	65	54	24%	2.07E+07	0.1
John's Folly Bay	52	14	22	18	82%	5.22E+05	1.9
Johnson Bay	77	21	32	27	82%	7.71E+05	1.9
Lameshur Bay	420	114	176	145	7%	6.22E+06	1.3
Leinster Bay	280	76	117	97	12%	4.97E+06	1.1
Maho Bay	187	51	78	65	38%	6.63E+06	0.5
Newfound Bay	31	8	13	11	0%	3.11E+05	1.9
Privateer Bay	40	11	17	14	19%	4.02E+05	1.9
Redezvous Bay	118	32	49	41	91%	8.70E+06	0.3
Reef Bay	556	151	233	192	19%	4.74E+06	2.3
Round Bay	118	32	50	41	66%	2.33E+07	0.1
Salt Pond Bay	72	20	30	25	23%	7.24E+05	1.9
Trunk Bay	88	24	37	30	35%	8.75E+05	1.9

Table D.5: St. John Nitrogen Loading Model maximum development conditions results

Bay	No. of buildings	Area of watershed (ha)	Total N load delivered to bay (kg of N per year)	Maximum total N load delivered to bay (kg of N per year)	Average total N load delivered to bay (kg of N per year)	% increase in N from current conditions	Bay Volume (m3)	Annual increase in nitrogen concentration (µmoles/L)
Brown Bay	157	126	555	684	620	1321%	4.66E+05	85.1
Caneel Bay	164	131	579	721	650	496%	5.19E+06	8.0
Chocolate Hole	45	36	171	198	184	0%	3.61E+05	33.8
Cinnamon Bay	227	182	759	998	878	427%	1.42E+06	38.2
Coral Harbor	813	652	2558	3573	3066	219%	2.57E+06	71.1
Cruz Bay	215	172	702	945	823	52%	2.53E+05	197.8
Fish Bay	747	599	2175	3283	2729	333%	1.63E+06	95.4
Friis Bay	36	29	128	158	143	1318%	2.93E+05	31.3
Great Cruz Bay	272	218	873	1195	1034	18%	9.56E+05	65.2
Grootpan Bay	214	171	712	940	826	832%	2.55E+06	19.9
Haulover Bay	35	28	125	154	140	528%	2.81E+05	31.9
Hawksnest Bay	112	90	433	492	463	477%	8.98E+05	34.4
Hurricane Hole	194	155	691	853	772	988%	2.07E+07	2.4
John's Folly Bay	65	52	239	286	263	165%	5.22E+05	32.7
Johnson Bay	96	77	348	422	385	155%	7.71E+05	32.2
Lameshur Bay	524	420	1742	2303	2023	1193%	6.22E+06	20.0
Leinster Bay	349	280	1244	1534	1389	1157%	4.97E+06	17.9
Maho Bay	233	187	776	1024	900	768%	6.63E+06	8.4
Newfound Bay	39	31	138	171	155	1342%	3.11E+05	31.8
Privateer Bay	50	40	178	220	199	1054%	4.02E+05	31.6
Redezvous Bay	143	118	487	630	558	28%	8.70E+06	4.0
Reef Bay	693	556	2049	3046	2547	974%	4.74E+06	30.9
Round Bay	148	118	527	650	589	385%	2.33E+07	1.6
Salt Pond Bay	90	72	321	396	358	996%	7.24E+05	31.6
Trunk Bay	109	88	374	479	426	810%	8.75E+05	30.5

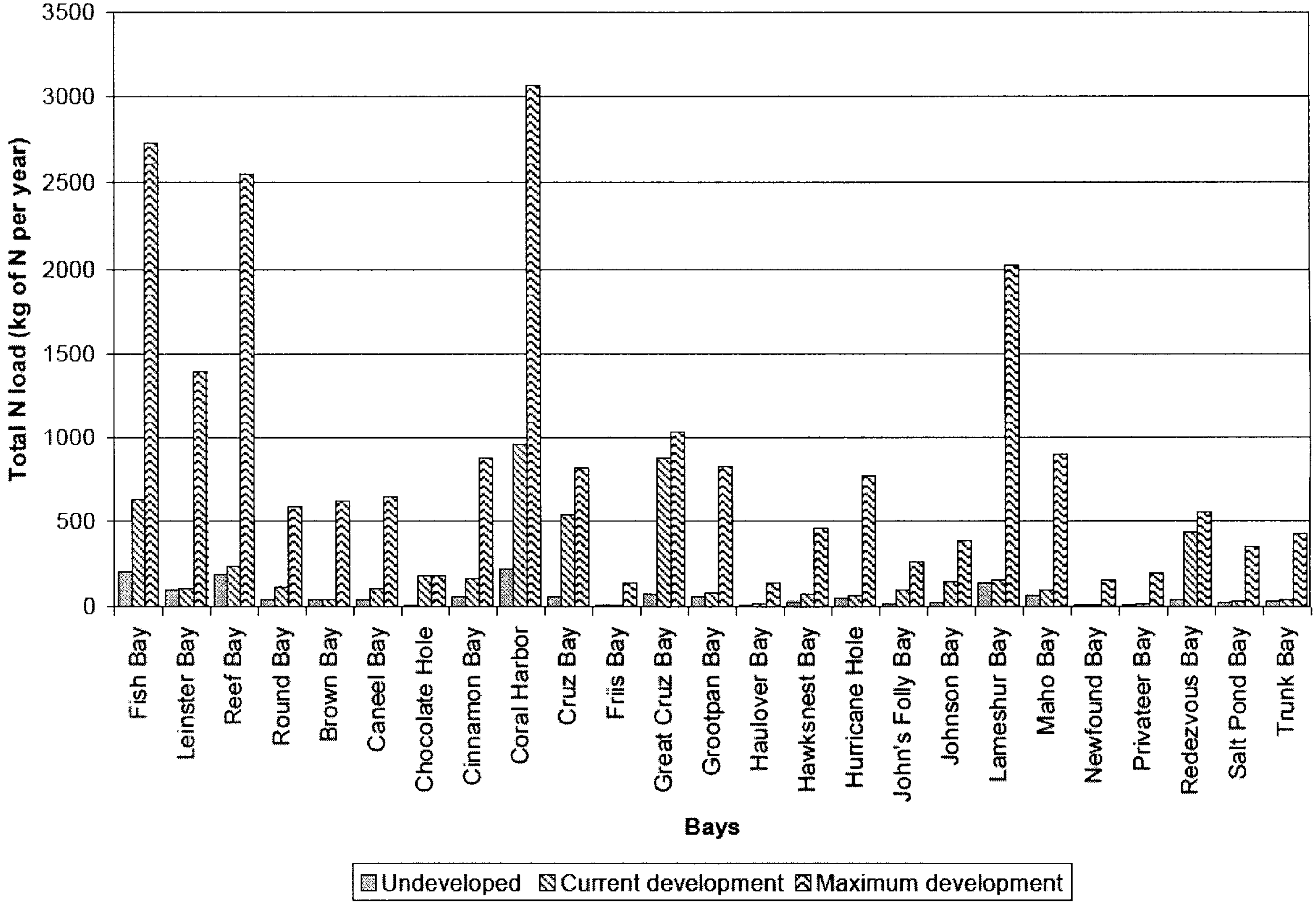

Figure D.1: St. John Nitrogen Loading Model results for undeveloped, current development, and maximum development conditions

E. National Park Service Historical Nitrogen Data

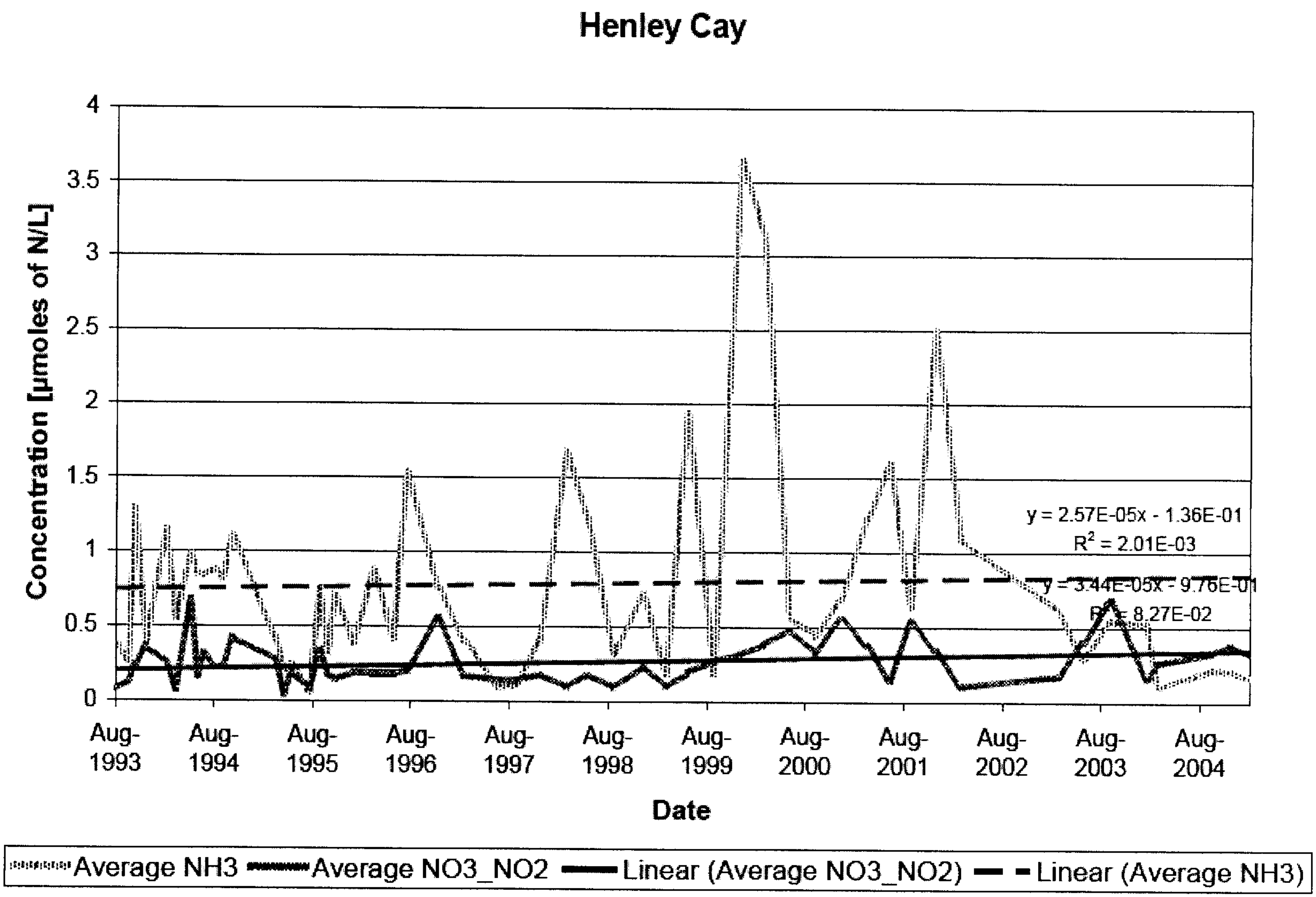

Figure E.1: Henley Cay National Park Service water quality data

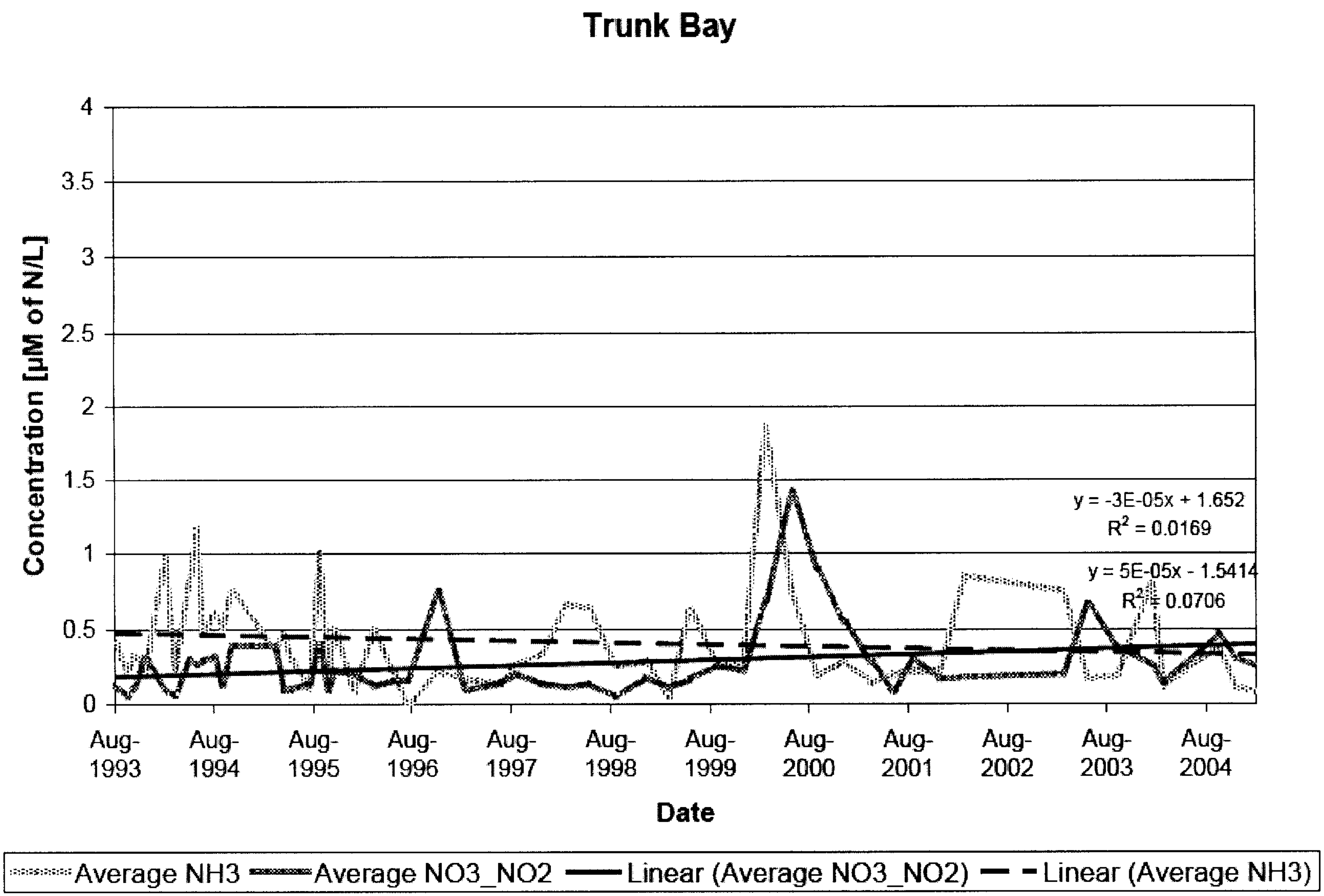

Figure E.2: Trunk Bay National Park Service water quality data

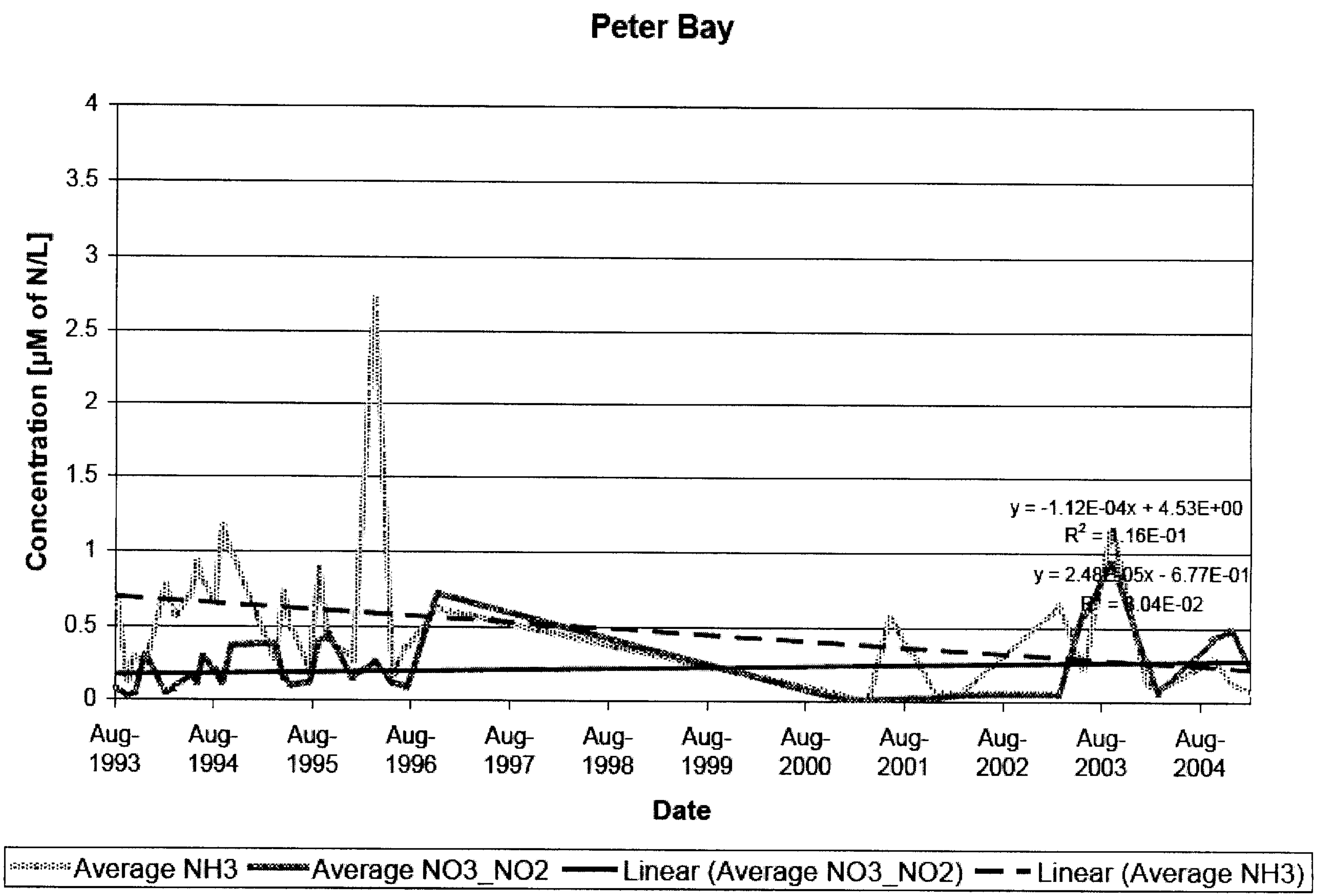

Figure E.3: Peter Bay National Park Service water quality data

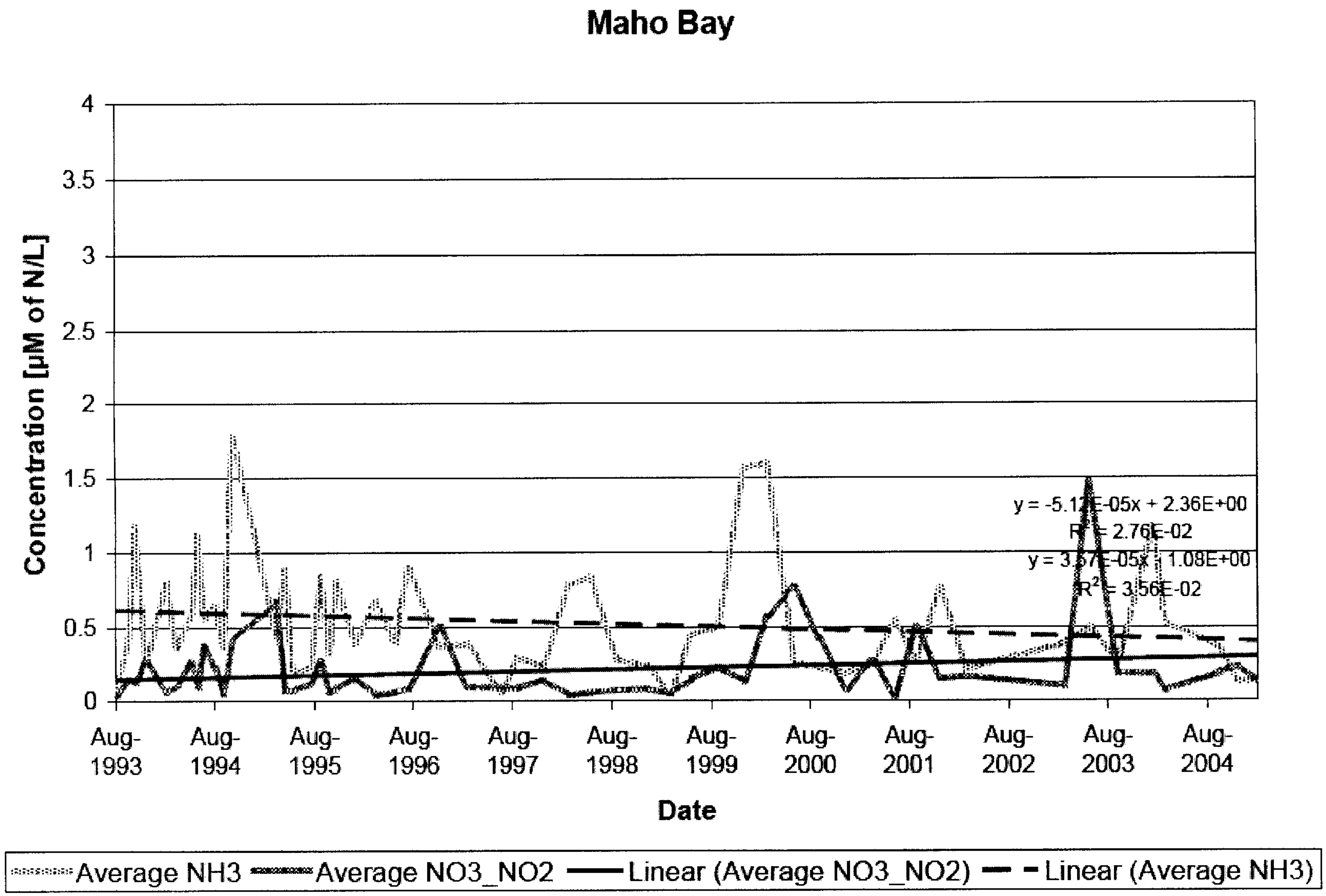

Figure E.4: Maho Bay National Park Service water quality data

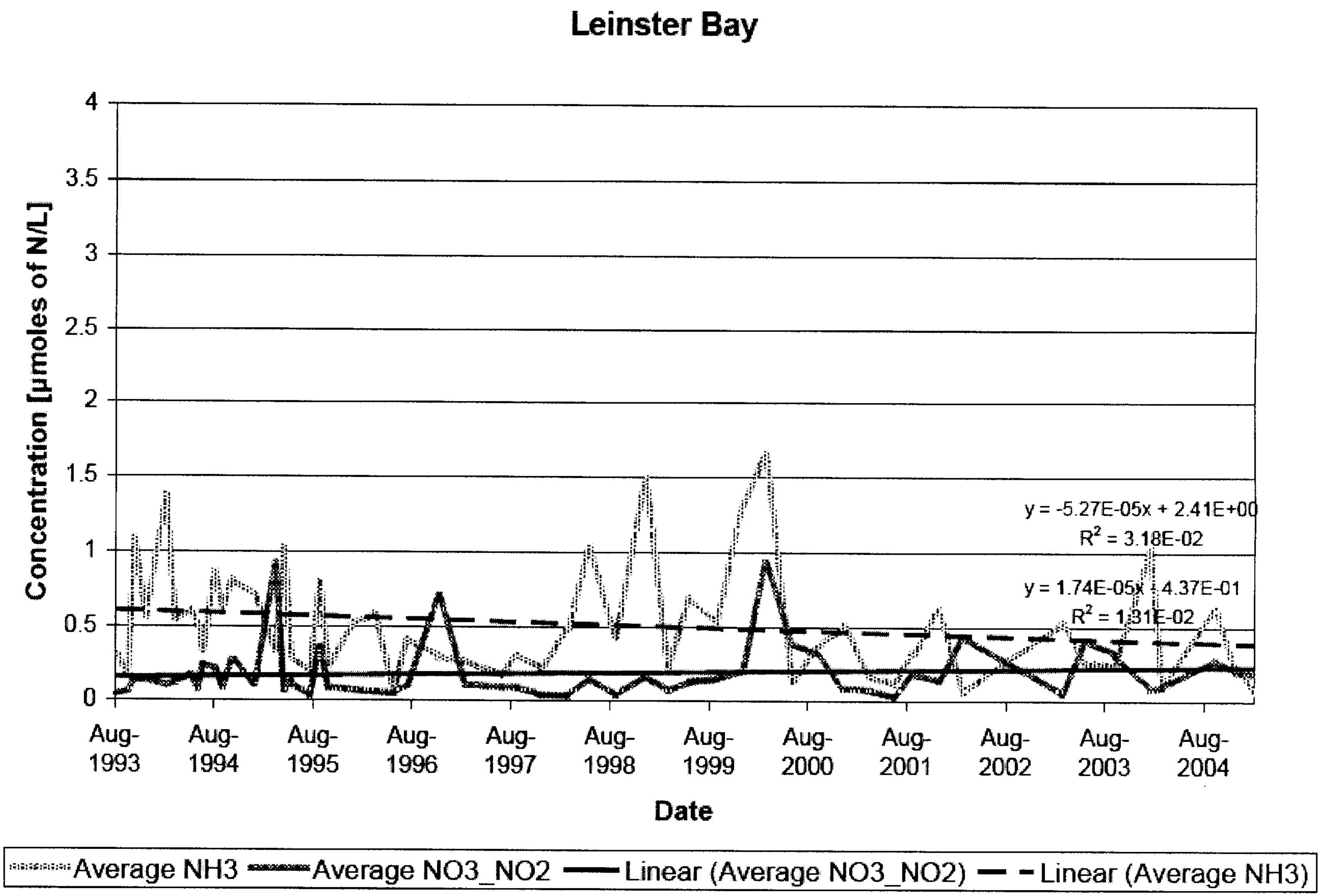

Figure E.5: Leinster Bay National Park Service water quality data

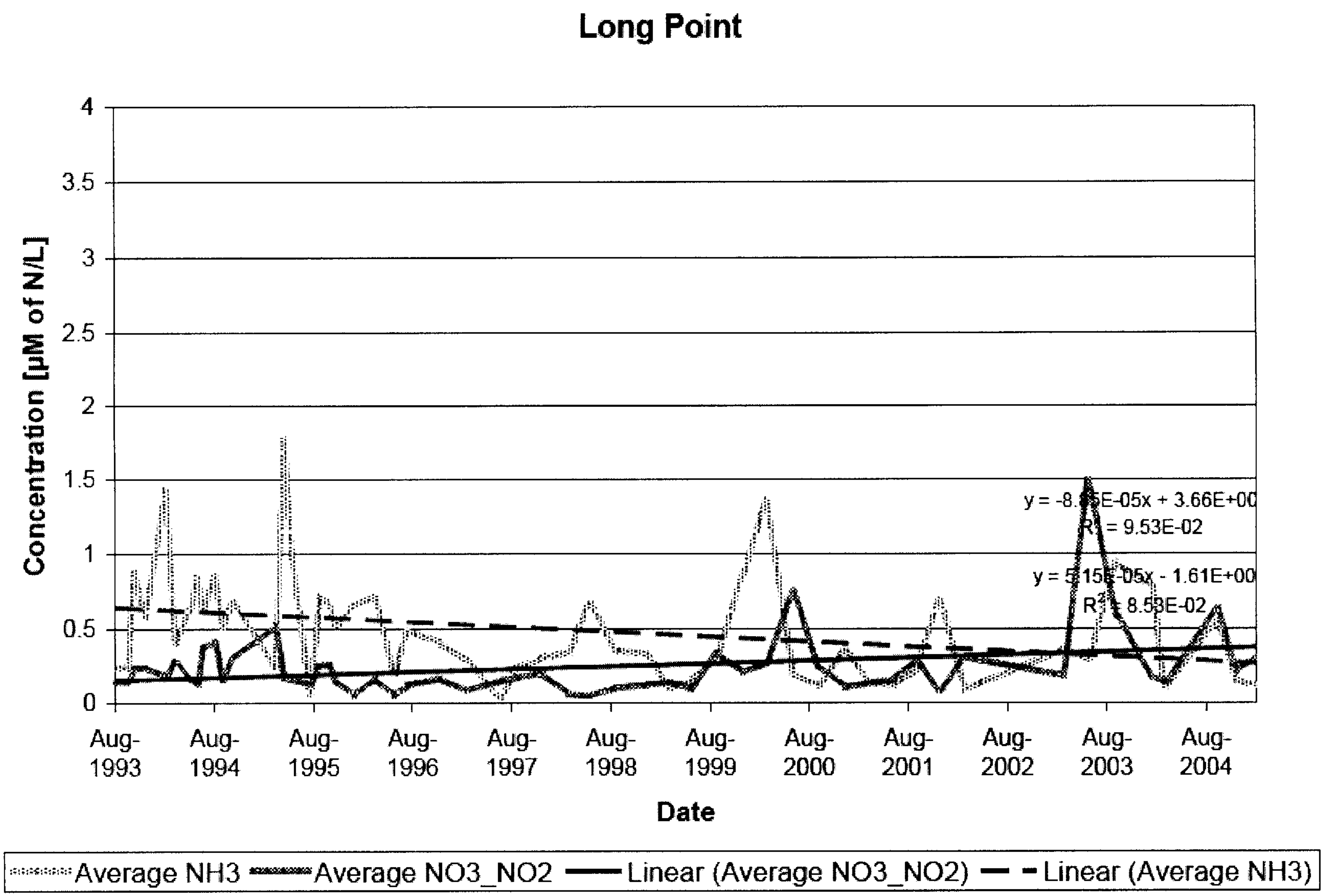

Figure E.6: Long Point National Park Service water quality data

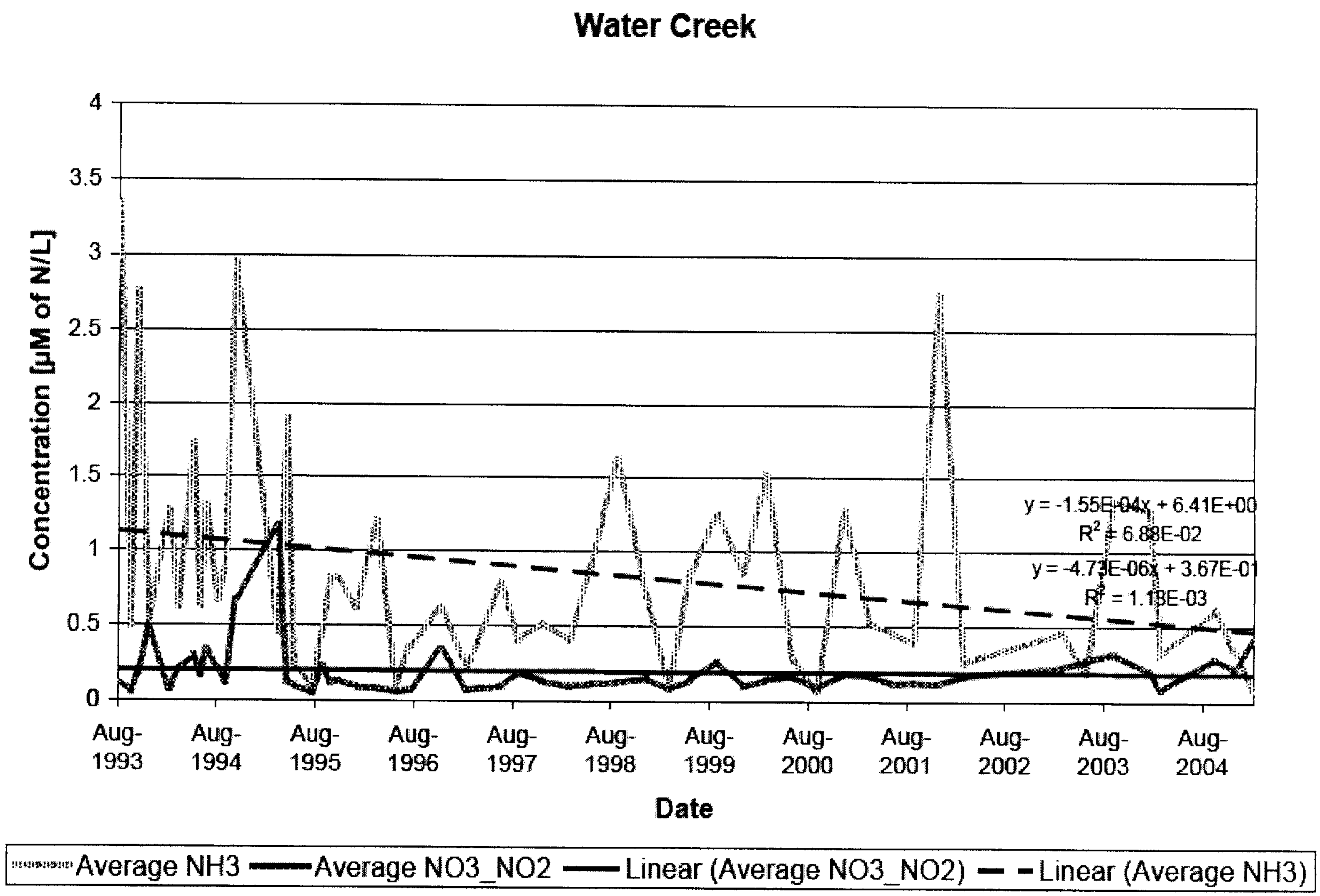

Figure E.7: Water Creek National Park Service water quality data

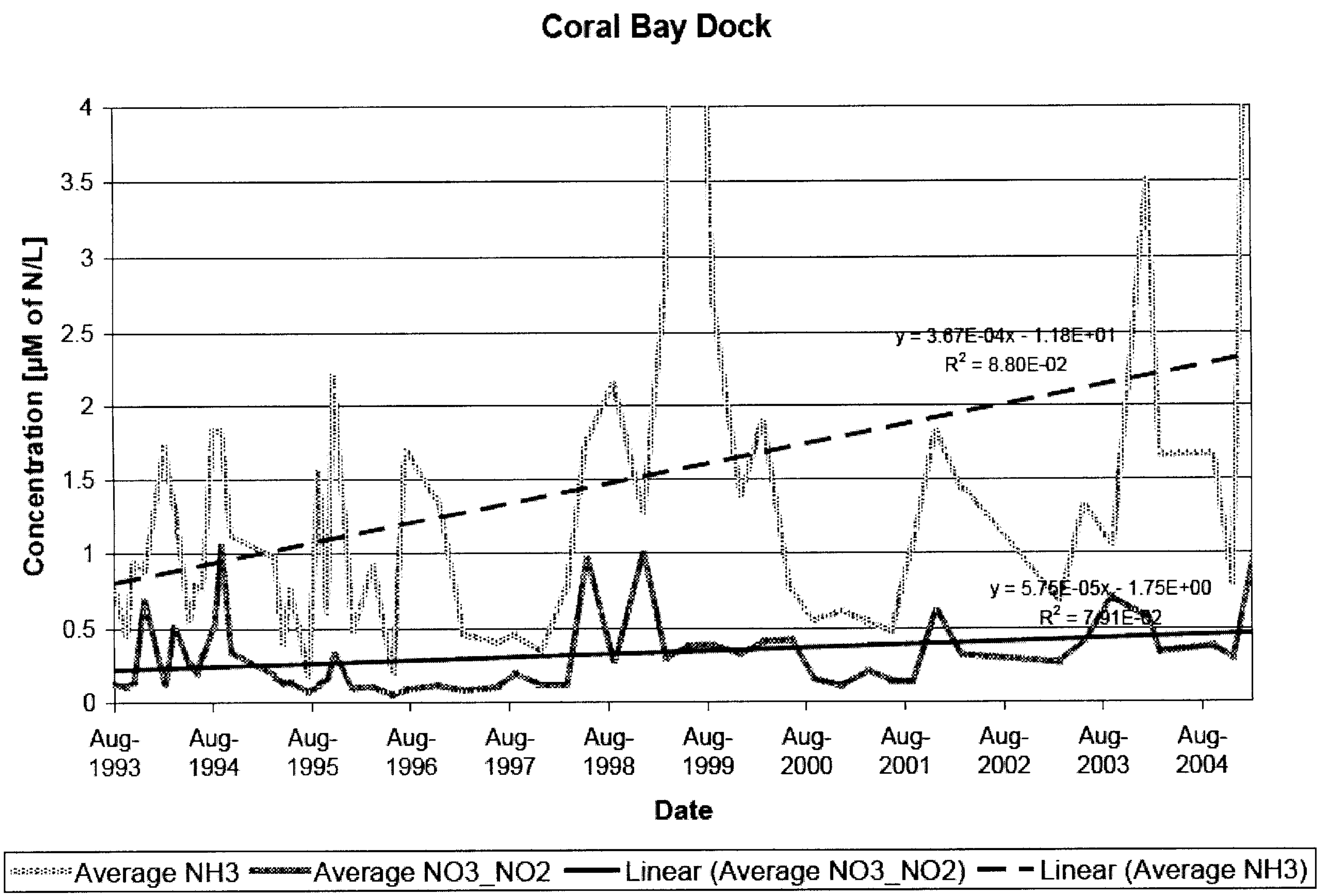

Figure E.8: Coral Bay Dock National Park Service water quality data

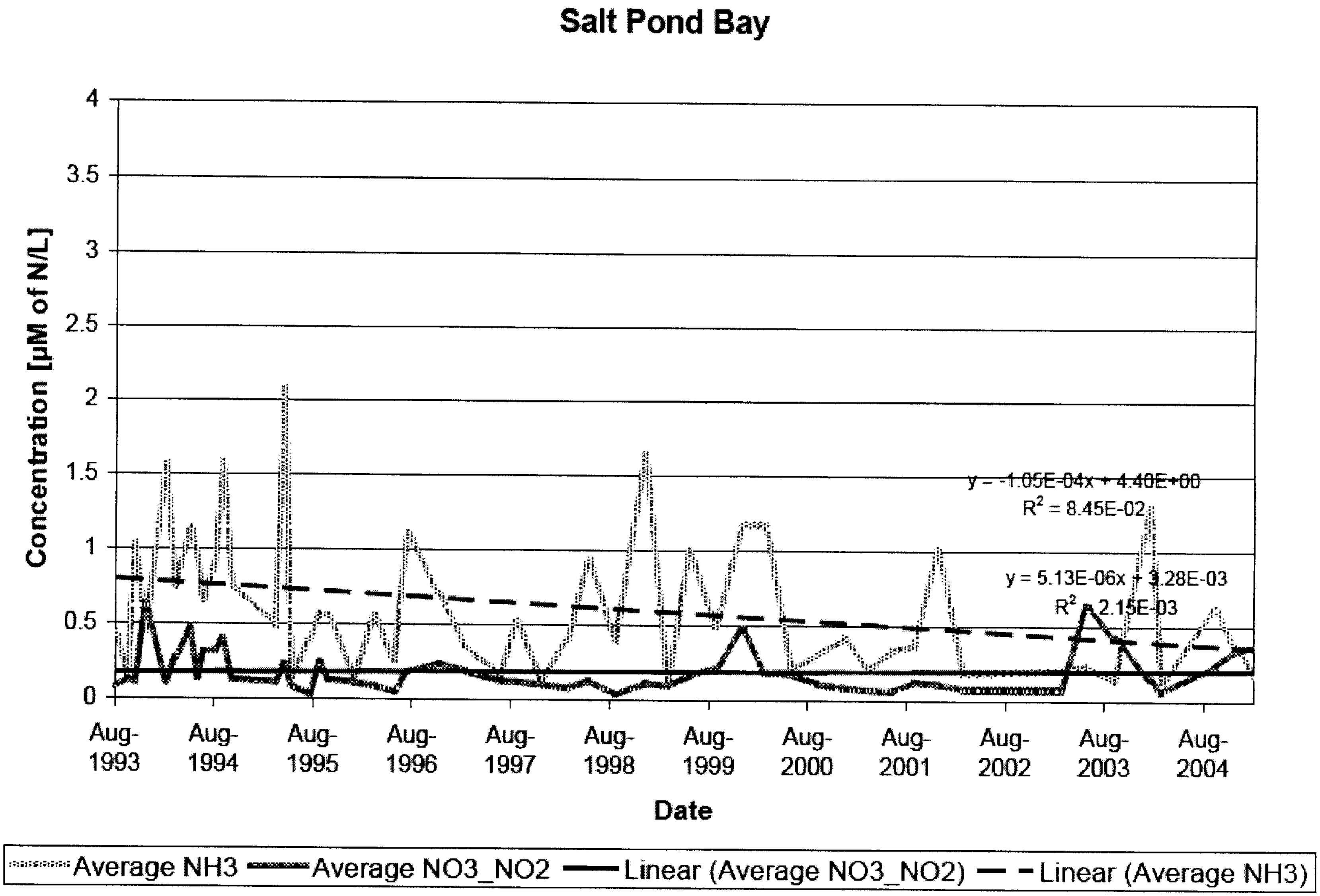

Figure E.9: Salt Pond Bay National Park Service water quality data

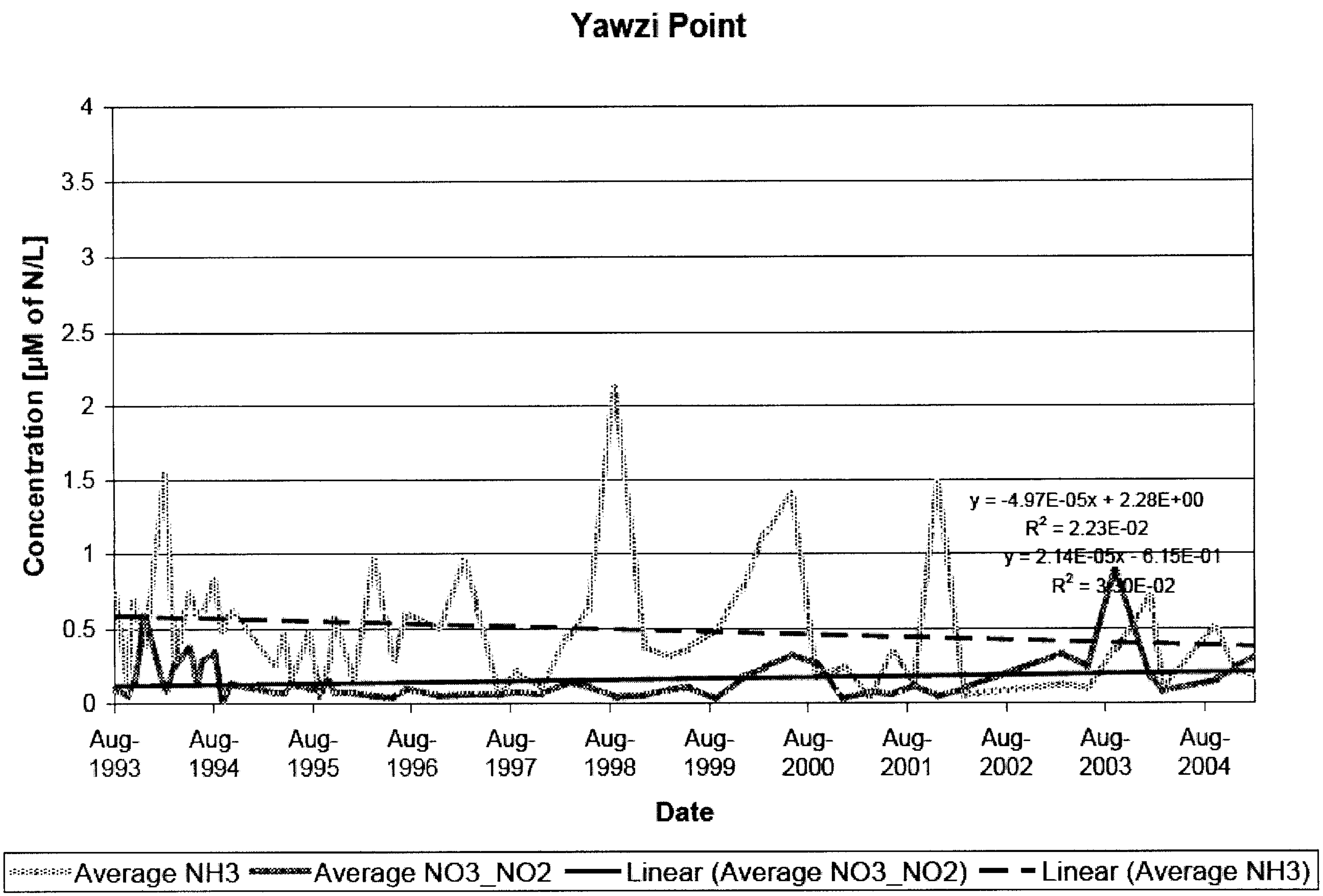

Figure E.10: Yawzi Point National Park Service water quality data

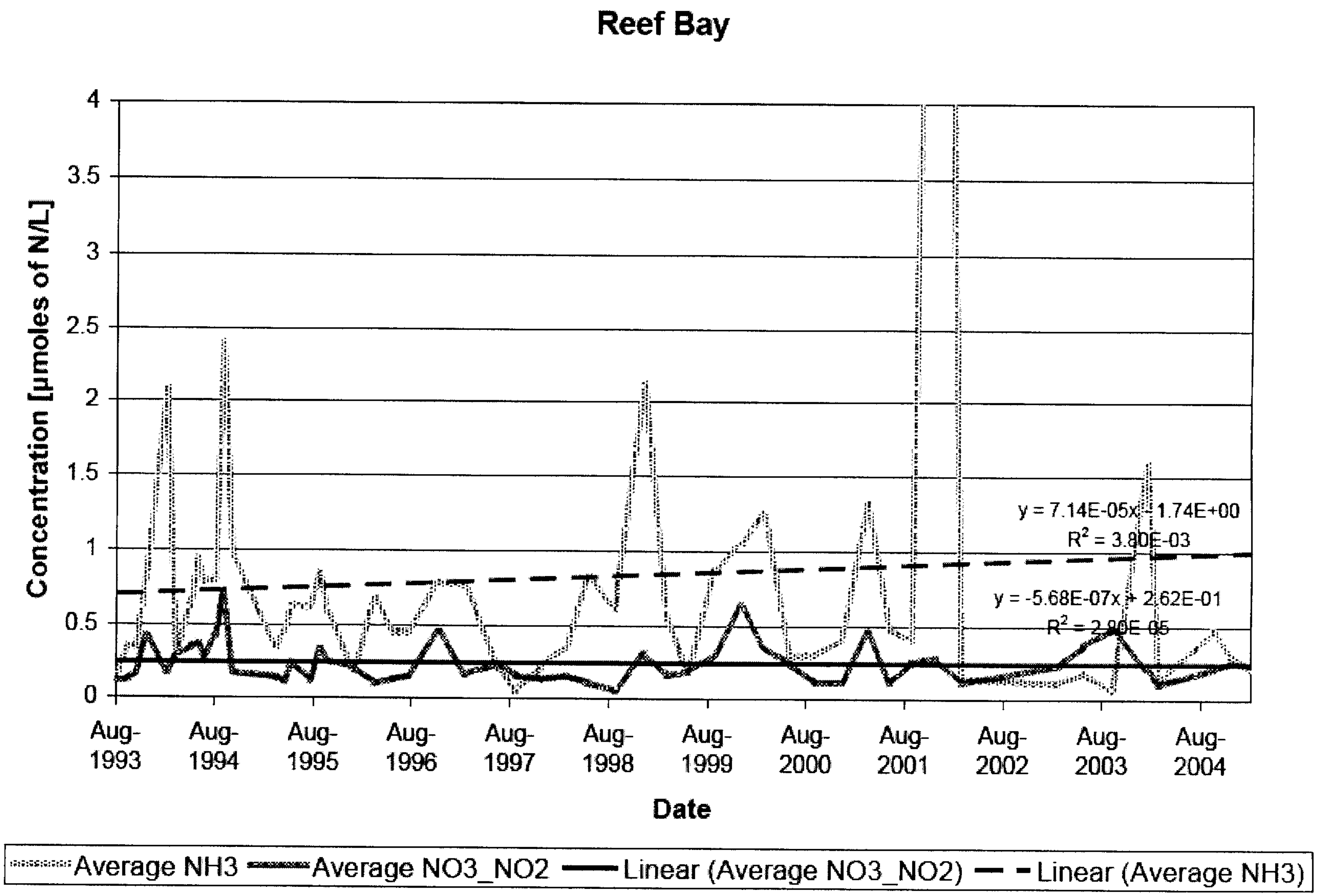

Figure E.11: Reef Bay National Park Service water quality data

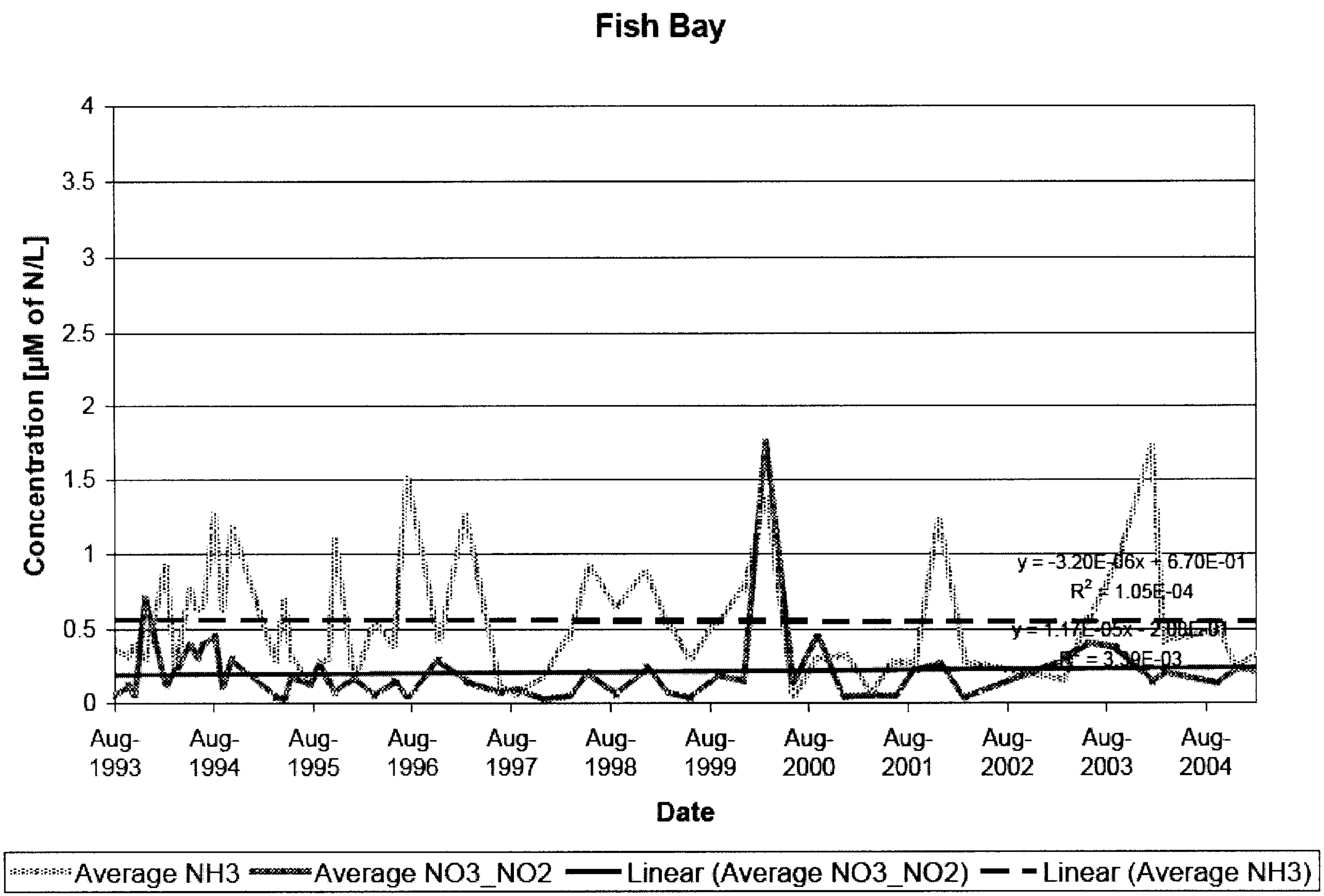

Figure E.12: Fish Bay National Park Service water quality data

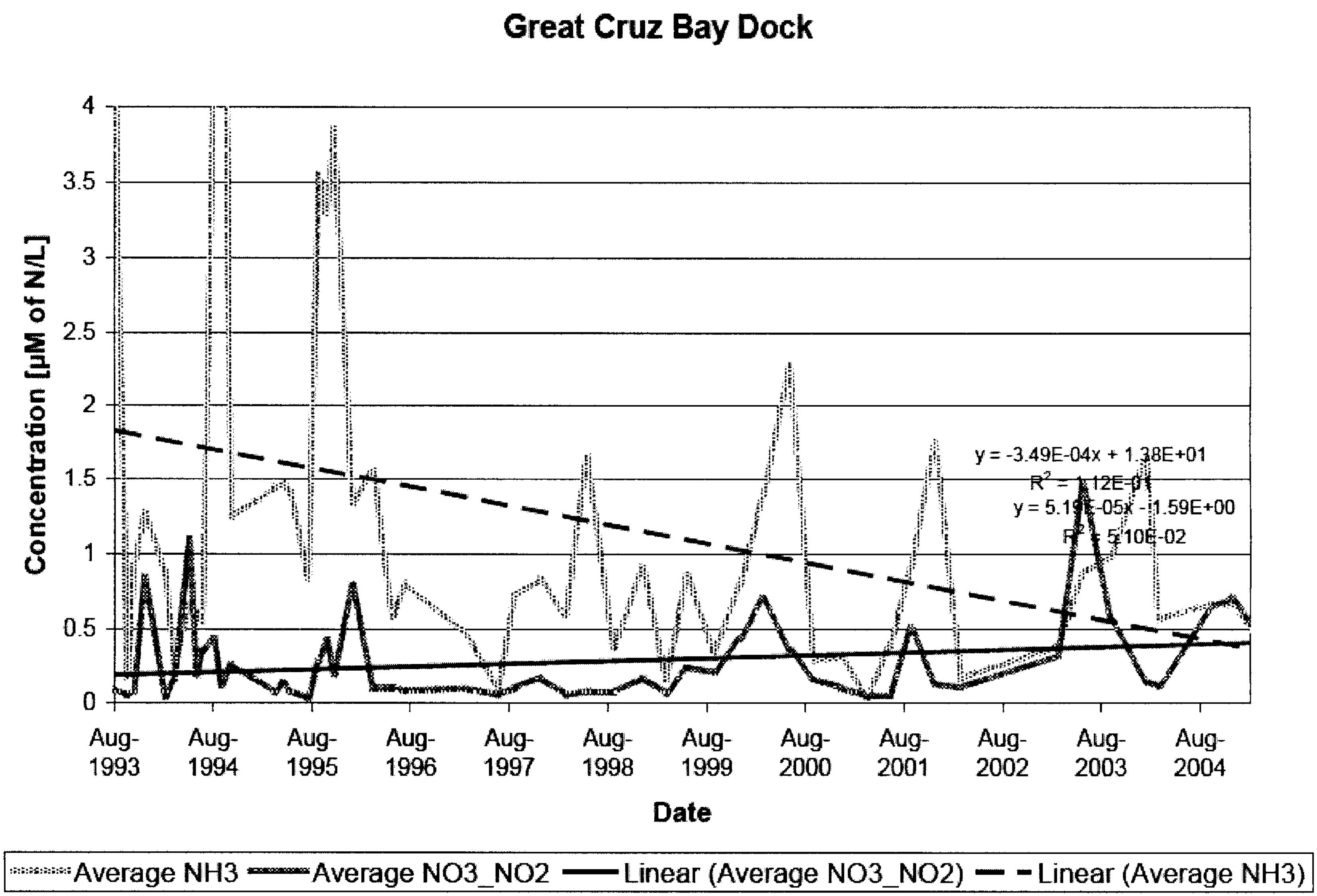

Figure E.13: Great Cruz Bay Dock National Park Service water quality data

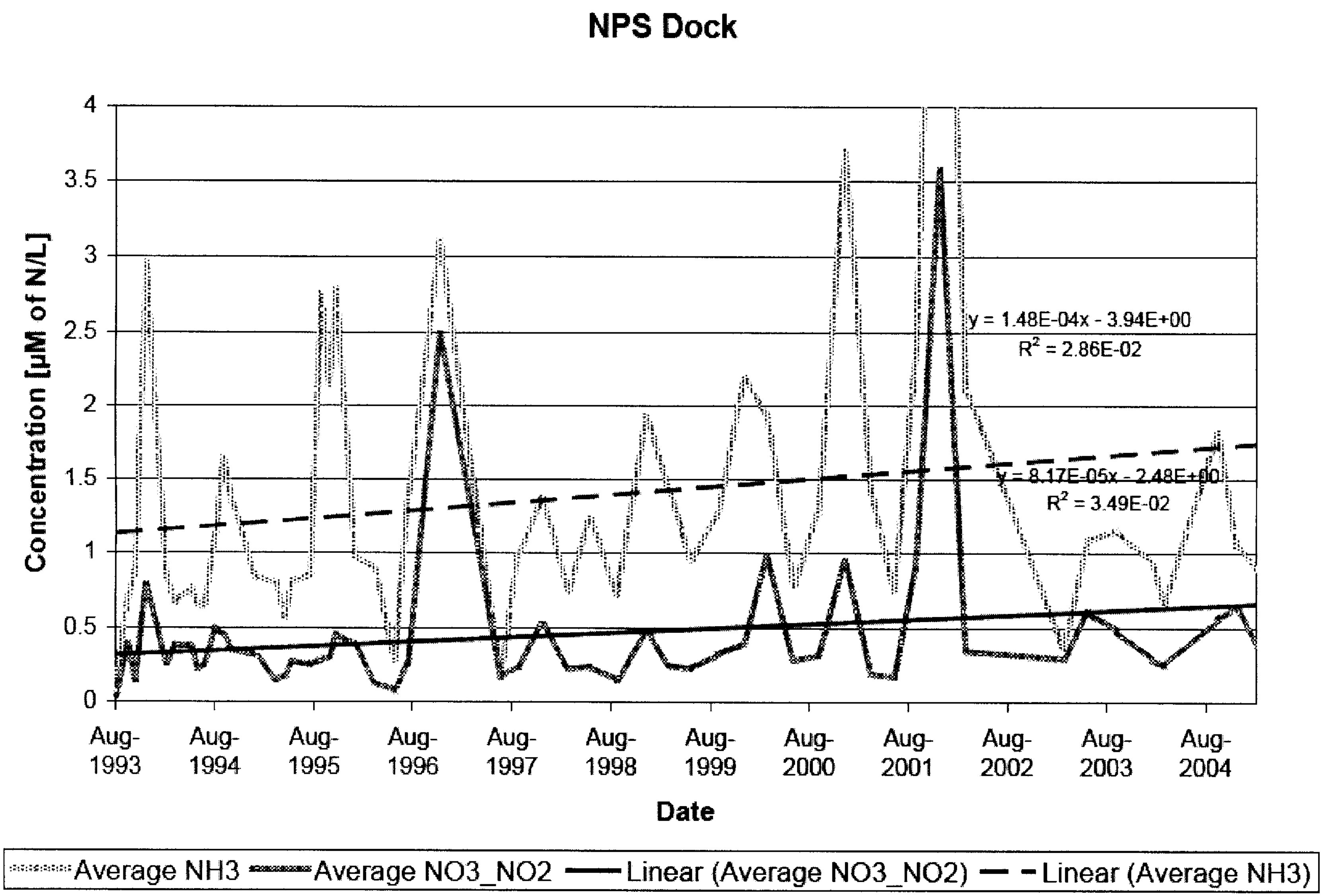

Figure E.14: NPS Dock National Park Service water quality data

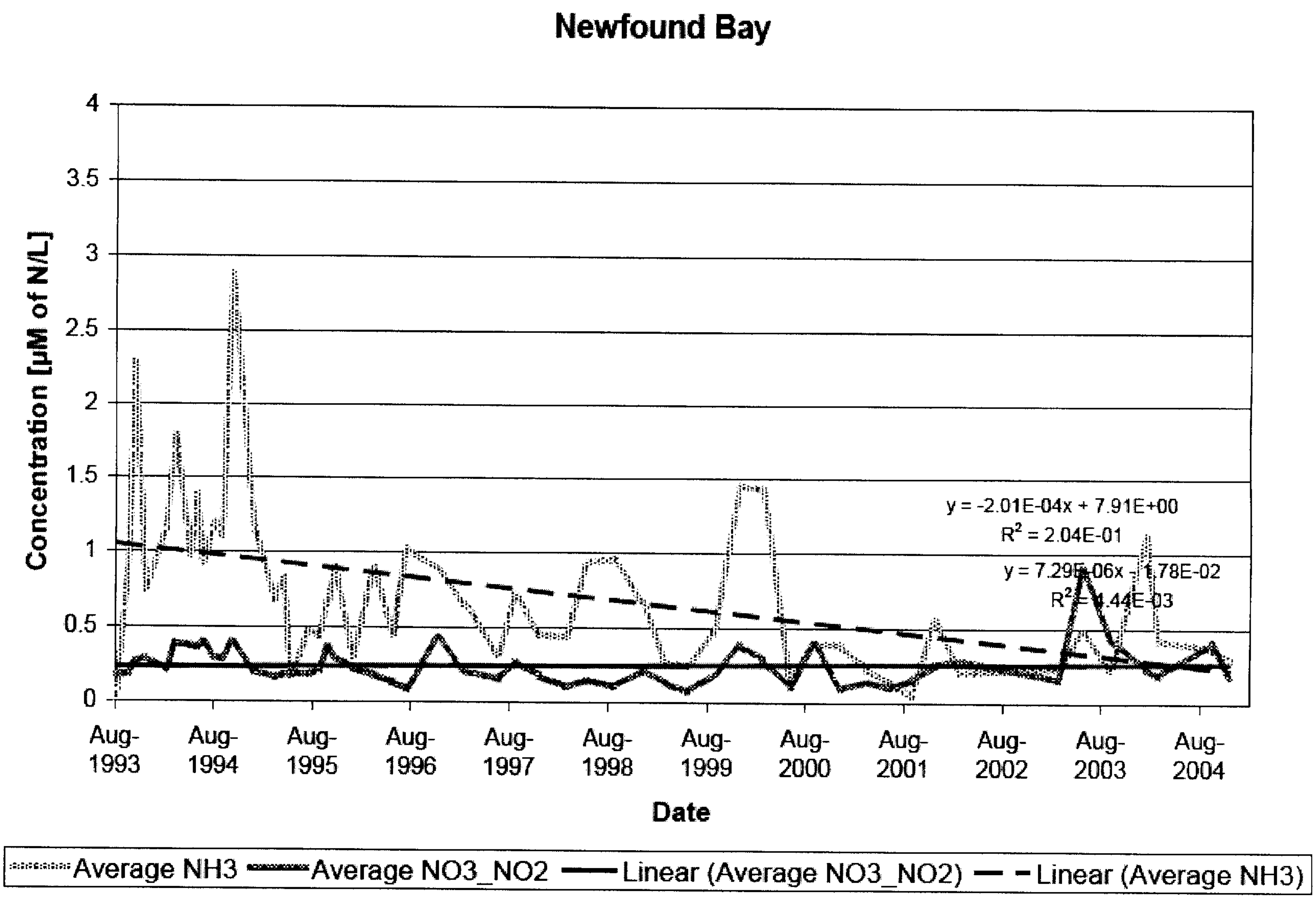

Figure E.15: Newfound Bay National Park Service water quality data

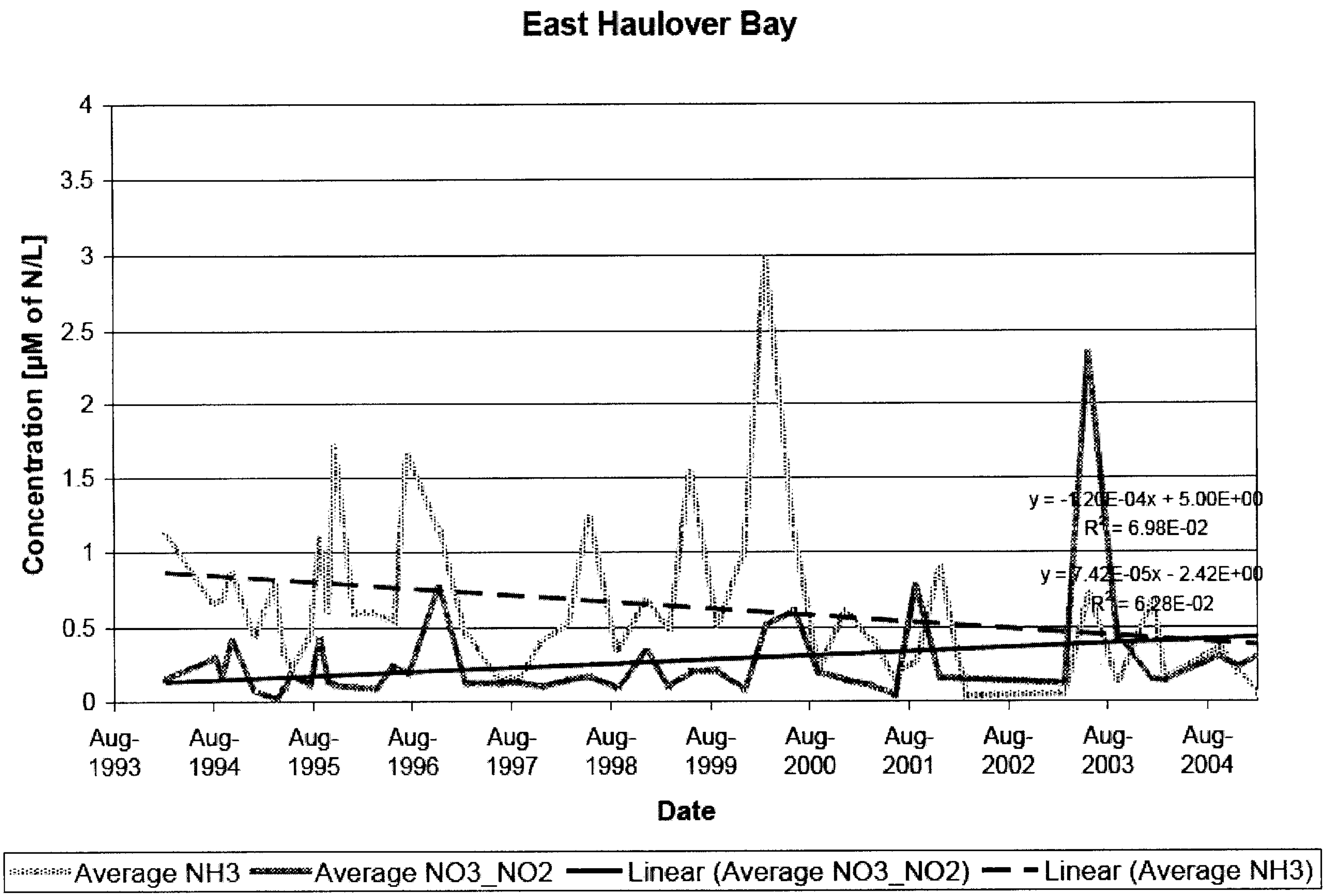

Figure E.16: East Haulover Bay National Park Service water quality data